With the permission of D. G. S. I.] [*Photo by Sir H. H. Hayden*

REVERSE FOLD IN STRATA OPPOSITE MOUTH OF KHARCINDARA, BEGAL, SAIGHAN, AFGHANISTAN.

[Frontispiece

CIVIL ENGINEERING GEOLOGY

BY

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Geological Survey of India

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TO

MY WIFE

PREFACE

THE foundations of British geology were laid, appropriately enough, by a civil engineer named William Smith, who, in his wanderings to and fro across England, noticed that certain kinds of rock could be followed for great distances in definite directions, whereas other rocks, usually in successive layers or beds, were normally met with along lines transverse to those directions. He observed that the several beds of rock were, in general, conformably superposed, also that they were sometimes irregular in thickness, and in some places unconformable to each other. He found that they frequently occurred in an inclined position, and were occasionally seen to be twisted and dislocated. He discovered that certain groups of strata contained distinctive fossils. Finally, he recorded his observations on an ordinary topographical map, and by using various paints with which to represent the different groups of strata, he coloured his map to show the position or outcrop of these several rock sheets.

It was perhaps natural that an observant engineer, familiar with topographical surveying, geometrical drawing, and solid projection, should thus make the first geological map, and incidentally lay the foundation of modern geology. William Smith has, therefore, been worthily called "the Father of British Geology." During the last hundred years these investigations into the physical constitution and history of the earth have been carried into various channels or branches. The more important branches of geology to-day are the examination of minerals and rocks, the study of the fossil remains of animals and plants, and investigations of the structure of the earth. As may be imagined, an elaborate nomenclature has also been evolved. Some of the technical terms and names now in use, even in structural geology, are unfamiliar and frequently unintelligible to the civil engineer. In consequence of this, he generally feels, when faced with geological problems, that the subject is too highly specialised for him to attempt a personal investigation. He therefore obtains the opinion of a geologist.

I have been fortunate enough to have been deputed on several occasions, in India, to assist engineers with advice in

regard to the geological aspects of various schemes—for water-supply, location of dams, alignment of tunnels, stability of hill-sides, choice of road and building stone, etc.

In 1921, I prepared a paper on "Some Engineering Aspects of Geology" for the newly formed Institution of Engineers (India). That paper has formed the nucleus of this book.

I am very greatly indebted to the Administrative Committee of the Institution of Engineers (India), not only for permission to reproduce a large number of the original drawings and all the photographs, but for the loan of the necessary blocks. These illustrations are acknowledged in the text with the words "by favour of I. E. I."

The Royal Geographical Society have kindly allowed me to use Figure 42 from my paper on Dr. A. M. Heron's "Report of the Geology of the Everest Expedition of 1921."

Photographs which are marked "with the permission D. G. S. I." have been lent to me by the Director, Geological Survey of India, to whom I am also indebted for sanction, with the consent of the Government of India, to publish this book.

Although the following pages have been written for those who are interested in this engineering aspect of geology, my purpose is best summarised in the words of Smeaton, who, in his *Narrative of the Building of the Eddystone Lighthouse* (London, 1813, page 136), said: "When we have to do with and endeavour to control those forces of nature which are subject to no calculation . . . it will be deemed prudent not to omit . . . anything that can . . . add to security."

C. S. F.

ROYAL SOCIETIES' CLUB,
ST. JAMES'S STREET, LONDON,
October 1922.

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INTRODUCTION

When an engineer is faced with the construction of a mountain railway, or has to "drive" a tunnel, "cut" a canal, or "found" a dam, he invariably endeavours to ascertain the kind and condition of the rock which his work will uncover, and he tries to assure himself that the rock will stand cutting, or otherwise prove satisfactory for the projected operations. In a large number of cases, an inspection of the ground, perhaps supplemented by the information obtained from "trial" pits, wells, or even borings, will give him the required data. In other instances, he feels it necessary to hold a consultation with a geologist before proceeding with the work of construction.

The commonest cases in which a geologist is asked for advice are with regard to

(1) the suitability of a given rock as material for road or building stone,
(2) the stability of strata in steep hill-sides,
(3) the structure of the beds and the condition of the rock likely to be met with in driving a tunnel,
(4) the structural features of dam sites,
(5) the water-tightness of a reservoir basin,
(6) the prospect of obtaining water under artesian conditions by wells and borings,
(7) the effect on the movements of underground water by interference with surface drainage.

In solving problems such as the above, a geologist bases his opinion on certain fundamental considerations. He may advise against the use of granite in a building exposed to fire, because the principal minerals—quartz and orthoclase felspar—have very different co-efficients of cubical expansion. Such a rock, when exposed to great changes of temperature, is liable to become friable and disintegrate. He might consider a hill-side unsafe because the bedding planes of the strata are inclined at such an angle as to render the superincumbent material liable to slide into the valley. He may find himself unable to recommend an

otherwise excellent dam site because the impounded water would cover a "fault," from which it may percolate into the workings of important mines. Thus it is seen that a geologist may, for one enquiry, make a careful examination of a thin section of a rock under the microscope: in another investigation, he will painstakingly measure the dips and strike of strata on a hill-side: in yet another instance, he may wander miles away from the locality for which his opinion is solicited. In all these cases his opinion may be considerably modified by other factors. The granite, for example, may be fine-textured and contain very little quartz: the strata of the hill-side may be massive, and the hill-slope re-entrant to the valley: the "fault" in the river-bed may traverse soft, impervious rocks, which might seal it against infiltrating water.

PART I

Water-Supply and Irrigation

CHAPTER I

GENERAL RAINFALL CONSIDERATIONS

WATER is perhaps the most important of all mineral substances for the support of life on the earth. In its normal liquid form it is not familiarly recognised as a mineral. It has a definite chemical composition, boils at 100° C., assumes the solid state at 0° C. and has other determinable physical properties which show that it fulfils the requirements of a mineral (see definition on page 115). A dweller in the arctic regions would also be fully justified in classing the extensive ice sheets there found as true rock masses (see definition on page 90).

The water of everyday life is kept in circulation on the earth's surface by the energy of the sun's heat. It is evaporated from water-surfaces and subsequently precipitated as snow or rain. Although available in the flow of streams which drain snow-fields and glaciers, direct rainfall is generally the most important factor in questions of water-supply and irrigation. Part of the rain which falls on the surface of the ground is discharged into streams and drains away. Some of the rainfall percolates into the ground, and either re-emerges in springs or replenishes the underground water. The remainder of the rainfall is lost by evaporation or absorbed by plants or by mineral substances in the soil and rocks.

This proportionate disposal of the rainfall of a given country is modified by several factors. The more important of these factors are the climate of the area concerned, the nature and slope of the ground on which rain falls, and the rate of precipitation of the rain. These meteorological aspects of the subject are as familiar to the engineer as to the geologist. Rainfall records are now available in most countries. These records show how great is the influence of mountains and how variable the rainfall can be in successive years in the same region. In large engineering projects, involving the use of the rainfall, it is necessary to determine the various percentages of the rainfall which are discharged into the streams or lost by evaporation and other causes, or which percolates into the ground. It may be essential to ascertain the rate of water-percolation through various kinds

of consolidated or unconsolidated strata. In some instances it is important to experimentally determine the capacity of wells. Most of this data is collected by the engineer. Without such information it may be quite impossible for a geologist to give an approximate estimate of the quantities of water which may be expected from a certain source in a given locality. It is unsatisfactory to assume that one-third of the rainfall goes into the streams as run-off flow another one-third percolates into the ground and that the remaining one-third is lost largely by evaporation and absorption by plants and mineral substances.

Run-off Flow.—Each of the factors, i.e. run-off, percolation and evaporation, etc., may vary enormously. The rain that falls on bare, hilly slopes composed of impervious strata such as clays, shales, etc., is almost entirely discharged into the streams and passes down to the valleys as flood or run-off water. It is likely that no run-off flow may result from light, intermittent showers on parched, level, sandy ground. On the other hand, a porous ground surface, composed of sand or scree or other loose rock debris, may become waterlogged by previous heavy rain and thus offer an impervious surface to later downpours. This subsequent rain would consequently drain away as run-off flow. It may thus happen that severe floods result from excessively heavy rain on otherwise porous catchments in a region of low total rainfall. A very instructive record of such phenomena is given on pages 28–32 of *Rainfall Reservoirs and Water-supply* by Sir Alexander Binnie.

The shortage of water which was experienced in England last year (1921), as a result of the prolonged drought, was not ameliorated by the few showers which fell at long intervals. In several places the ground water-level fell considerably. Countries subject to a tropical climate, with alternate wet and dry seasons (monsoon periods), suffer more severely by abnormal conditions of rainfall. A failure of the wet season, due to an irregularly distributed, abnormally low rainfall, may be the cause of famine in a wide tract of country. Each region and each area of that region has its own peculiarities of climate, ground surface and rainfall, which require detailed investigation. The rate and duration of rain precipitation are in general more important than the total annual rainfall. For example, heavy downpours may cause floods in desert regions, whereas light showers may be the blessing of a fertile area, although both tracts have the same annual rainfall.

Percolation.—The percentage of the rainfall which sinks into the ground depends very largely on the nature of the ground upon which the rain falls. The greatest quantity will sink into

a dry, cool, porous soil on level ground. None may be absorbed by a damp, bare, impervious surface on a steep slope. Between these extremes varying amounts will percolate into the ground. The percentages in the several cases will be influenced by the degree of porosity of the soil, the presence of vegetation, the declivity of the surface, the temperature and humidity of the air and by the rate of precipitation of the rain. Forests, wooded tracts or grassy areas are, as a rule, not as good as open ground for the percolation of rain-water. Granitic rocks, gneisses and schists, slates, shales and clayey strata are generally impervious unless deeply weathered or fissured. Basaltic lavas, such as those of Antrim (the Giant's Causeway) and other areas, although impervious in texture are frequently traversed by numerous contraction joints. Hard quartzites and fine-grained sandstones are also impervious in texture unless heavily shattered. Soft or coarse-grained sandstones, gravels and boulder beds are excellent sources from which to obtain underground water if suitably located. In some tropical countries, the peculiar weathering product of rocks known as laterite occupies wide areas, usually as a capping to plateaux, and holds large volumes of subterranean water. Limestones are known the world over for the abundant supplies of *hard* water which are occasionally obtained from great caverns and fissures which occur in certain massive varieties of such rocks.

All the water which enters the ground by percolation tends to gravitate downward until it re-emerges at the surface as spring water, or passes into the stationary ground water which lies below the surface at varying depths under different places.

Evaporation.—The percentage of the rainfall which is lost by evaporation varies greatly but is largely influenced by the climatic conditions of the locality. An area subject to a dry, hot climate, low, average rainfall, long periods of sunny weather and a strong prevailing wind, is almost certain to have large losses by evaporation. In some parts of the cotton-growing areas of western India these losses are probably as high as 60 to 72 inches a year. What a loss of 6 feet means to the efficiency of a reservoir in such an area can be gauged from the adjoining Fig. 1. In this case $L =$ length of water-spread, $B =$ length of dam at the water's edge and $D =$ maximum depth of the reservoir. Assuming the shape to be as regular as drawn, the volume of water in the reservoir is $L \times B \times D \div 6$. If the evaporation loss is one-tenth of the depth, i.e. $D/10$, then the volume of water remaining in the reservoir will be $9/10\, L \times 9/10\, B \times 9/10\, D \div 6$. This is 729/1000 of the original volume. The loss from the reservoir is therefore 27·1 per cent. If the evaporation losses

lower the height of water in the reservoir by 1/4 D, then the volume of the remaining water will be 27/64ths of the original volume. This would mean a loss of over 57 per cent. From these hypothetical calculations it is at once evident that for such areas shallow reservoirs would be least economical. To cope with a loss of 25 per cent. in an area subject to an annual evaporation loss of 6 feet, it would be necessary to build a dam to hold at least 60 feet of water (in a reservoir similar to that illustrated in Fig. 1).

Absorption.—The amount of water absorbed by growing plants or by the mineral components of rock during the process of weathering is seldom large. Under certain abnormal conditions, however, appreciable losses may occur. For example,

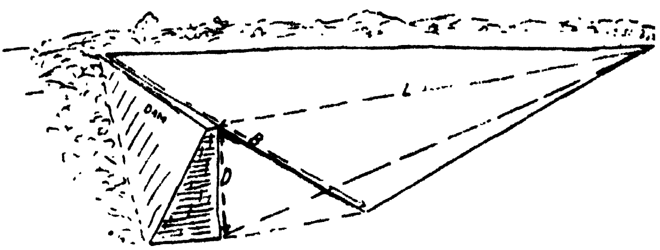


Fig. 1.

Part section of a reservoir.
L = length of water-spread.
B = length of dam at water's edge.
D = maximum depth at dam.

certain clays which shrink enormously under the baking influence of the fierce heat of the sun absorb large volumes of water before they really become wet. The water thus absorbed is strongly held in the interstices of the clay and is only given up when exposed to further scorching in a hot sun for many days. This clayey ground cracks in great fissures 1 to 12 inches across and several feet deep where the clay is thick. Such water is consequently not available for supply purposes. When wet, such clays form an excellent floor for a reservoir but are liable to certain disadvantages. If stirred or disturbed by the movement of currents in the reservoir, this clay, which is exceedingly fine, renders the water muddy by becoming suspended in the water, and requires special treatment for its precipitation.

CHAPTER II

RIVERS AND CANALS

THE artificial channel is usually so constructed that the water is conducted in more or less straight courses at a relatively low velocity. The gradient of the cutting being low and the banks to some extent protected there is practically no erosion. Mountain streams, generally, have straight courses; but their gradients are usually very steep and their waters come down in a torrential discharge. Such streams are continually carving out their beds, deepening their channels and lengthening their courses in an endeavour to reduce their gradients. Large rivers in flat alluvial country, on the other hand, usually flow gently in tortuous courses; they, however, invariably scour their concave banks and deposit their load of sand and silt below convex bends. They may, by raising their beds with deposits of silt, threaten to wander from their channels and flood the surrounding country.

The cutting action of a stream depends on various factors—the gradient of the river bed, the volume of water being discharged, the load of abrasive material either in suspension or rolled along by the stream, and the structure and hardness of the rocks which constitute its bed and banks.

Gorges.—A stream which is actively eroding its bed or banks may be deflected from its course in various ways: e.g. by a belt of hard rock, by following a band of softer strata, such as the crushed rock in a zone of faulting. If it flows through country composed of soft uniform rock, it may hold its course and excavate a deep ravine, or a gorge, or a canyon. All steep-graded streams must lengthen their courses to reduce their gradients and in so doing they cut far back into the hills; they may even cut back across a mountain range and enlarge their drainage areas by absorbing the drainage of other streams. Examples of this kind are to be found in almost every country. They may occur within the limits of a small country, or they may be on a vast scale. In the Himalayas the south-flowing rivers have, in many cases, cut through the main range in impassable gorges and captured streams from the Tibetan drainage system.

Occasionally, a stream which issues from impounded water such as a lake, may have a steep out-fall. If the flow is sufficiently

maintained, and the cutting action of the water below the out-fall moderately rapid, a gorge will be carved at the out-fall and the lake completely drained.

Terraces.—When a large mountain lake is destroyed in the manner described above, the main stream may continue to erode its channel down the middle, or on one side, of the lake bed. In many large lakes there is a deposit of gravel and silt on the floor of the lake. Thus it may happen that some of this gravel material may be left on the sides of the stream which is flowing through the old lake floor. These residual beds of gravel and silt will constitute "terraces." Terraces of this description are sometimes found hundreds of feet above the beds of great rivers in deep valleys. They are an indication of the enormous amount of cutting that may be performed by rivers in mountainous country.

It is well known that steady, slow earth-movements are operative in various parts of the world. Large areas may be gradually depressed, other tracts may be slowly elevated. In regions of up-lift, low-velocity streams may have their gradients increased and so-called rejuvenation of the streams take place. The streams once again begin to carve out their beds, possibly in the very silt they may previously have deposited. In process of time, if a stream cuts its bed as fast as the rate of uplift, the silt beds will appear and form river terraces on its banks. Terraces of sea pebbles and gravel are often seen on the sea-shore; these are generally the result of a rise of the land and a regression of the sea.

"Bars."—A river deposits its load of gravel or sand or silt when the velocity of its flow is diminished. Pebble and boulder beds are generally found where mountain rivers debouch on to the plains; gravel and sandy deposits occur lower down the river, where the gradient of the bed is less and the stream velocity unable to carry coarse material; and the finest silt is usually precipitated in estuaries and deltas or carried out to sea. The rise and fall of the tides produce, alternately, decreased and increased velocity in the flow of a river. There is deposition of silt in the slack water at flood tide, followed by renewed movement of the detritis during the ebb. It is for this reason, chiefly, that the tidal, lower courses of big rivers have shifting sand-banks and bars. Their navigation becomes more difficult if the problem is complicated by the existence of important tributaries or the presence of ocean currents across the mouth of the river. Combinations of these physical factors are responsible for the "sands" in many rivers and for the "bars" across various harbours (e.g. the James and Mary sands in the Hugli and the bar across the entrance to Durban harbour).

In the case of very large rivers, e.g. the Hugli below Calcutta, it is frequently impossible to actually control the stream channel, which is kept open by dredging. In other rivers, elaborate protection works can often be built at a reasonable cost. The building of walls perpendicular to the banks of a stream (i.e. groynes) to prevent scour generally produces too sudden a check on the flow of a stream. This resistance reacts by the appearance of fresh scouring, either below the "groyne" or further up-stream. Experience shows that streams are more effectively constrained by building "training walls" or embankments almost parallel with the channel and deflecting the current gradually through successive small angles.

Fluctuations of the Ground Water-level.—The experience which has been acquired in sinking wells and putting down borings shows that stationary ground water occurs almost everywhere below the surface. In some areas this ground water lies at great depths; in other places, it may be close to the surface. After a prolonged spell of dry weather, an appreciable fall in the ground water-level may take place. Similarly, a continuous period of rain may result in a rise of the ground water-level. These fluctuations of rise and fall may vary from a few inches in fissured rocks to over 50 feet in porous strata.

Ground Water under Streams.—The ground water-level generally appears to be nearer the surface under river beds than elsewhere in a given area. The phenomena met with in various places is suggestive of percolation from the river to the ground water. This transfer of water tends to raise the level of the ground water to that of the river. Under most rivers there is an underground flow or seepage of water immediately under, and parallel to, the river bed. This underground flow would probably be continued long after the river bed is dry. In cases where sand or porous rock underlies the bed of a stream, this underground flow can often be easily detected.

If the thick, alluvial deposits of an area are impregnated with saline matter, it is almost certain that the water from wells in this region will have a brackish taste. The washing action of the subsoil water under the river beds of such an area will generally have removed the saline matter from immediately beneath the river channel; consequently, when the river runs dry, *shallow* wells dug on the banks, or in the river bed, should furnish "sweet" water. If these wells are too far from the river or sunk too deep in the river bed, they will tap saline water. Fig. 2 illustrates this point; it represents the cross-section of a river channel, and shows the position of good and bad wells.

Care of Surface Drainage in Saline Tracts.—In areas

where the underlying alluvial strata is impregnated with saline matter, it is unwise to interfere with the surface drainage without a careful consideration of the results which may follow such an operation. Suppose, for example, a dam were built across a stream and the run-off flow of the stream impounded, leakage below the dam might continue to maintain the underground stream flow and shallow wells in the stream bed would perhaps not be affected : if, however, the dam foundations effectively prevented leakage, the underground flow would diminish, saline water would gradually return to the stream bed, and villages lower down-stream would find that their shallow stream-bed wells were becoming contaminated with saline water. In process of time, the contamination would render the water of down-stream wells as brackish as that of those wells which are away from the stream (see Fig. 2). The cleansing action of centuries of percolation would thus be rapidly undone. If there are no villages dependent, during the dry seasons, on the shallow wells

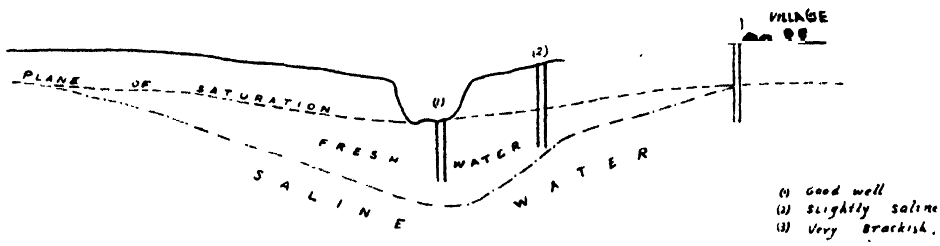


Fig. 2.

Section across a river in an alluvial saline tract.

of a stream bed and the impounded water of the stream is urgently required for irrigation purposes, the change in the direction of the sub-soil drainage may not be detected ; but the engineer at least will know what is likely to happen when the dam is built.

The Underground Water below Canal Beds.—When an unlined canal is cut through porous ground, it will—when put in operation—cause the ground water-level in its vicinity to gradually rise. There will be leakage from the canal to the ground water. If the subsoil is impregnated with saline matter or the ground water is saline, there is danger of the soil itself becoming contaminated from these sources.

The Formation of Alkali Soil.—Enormous quantities of saline matter are liberated, or result from, the denudation and decomposition of rocks. Most of these salts are soluble and are carried into the rivers and into the subsoil waters. In some cases, as in Rajputana, wind-borne salt is carried inland from the sea and deposited on the land. From such sources the under-

ground water may become heavily charged with various salts, particularly calcium carbonate, magnesium carbonate, calcium sulphate, magnesium sulphate, sodium sulphate and sodium chloride. Saline water if brought close to the surface, particularly in a dry, hot country, may be drawn up into the soil by capillary movement. The water will be evaporated by the sun from the ground surface and the saline matter will be left in the soil. The yearly wash of the rains may not remove the saline matter from the soil. Gradually the soil will become saturated with these salts, some of which are poisonous to vegetation ; consequently the country will become barren. Thus it is possible that in an endeavour to irrigate one area another may be rendered sterile.

Similarly, a rise of the ground-water level may occur on the down-stream side of an area which is being over-irrigated—the surplus irrigation water will tend to raise the level of the underground water. If this is contaminated with saline matter, the processes described in the previous paragraphs might also occur and result in the deterioration of valuable country. Thus it is possible that under certain conditions the processes of irrigation, e.g. the over-irrigation of one area by means of unlined canals, may produce alkali soil in two areas, one *above* and one *below* the area which is being irrigated.

The Prevention of Soil Deterioration by Alkali.—In alluvial tracts, where saline matter is known to be present, there are two urgent considerations with regard to the use of canals for irrigation purposes : (1) that the distributing canals should have impervious channels (i.e. lined canal beds in porous ground) above the point of actual distribution, and (2) deep unlined or infiltration channels from and below the area under irrigation ; the idea, in the two cases, being to prevent the ground water-level rising too close to the surface of the ground and thereby impregnating the soil with various salts which are harmful to plants.

Preliminary tests should always be made to ascertain whether the underground water or the subsoil contains saline matter. If salts are present, it is wise to incur the extra cost of lining the canals and in providing suitable draw-off channels. The appearance of alkali in places in Northern India has resulted in the destruction of large areas of valuable agricultural land. The only remedy to save—or at any rate arrest—the accumulation of alkali in the soil is that of lowering the ground water-level, and thereby preventing evaporation and subsequent capillary movement of salt-bearing ground water. An elaborate system of pumping, by erecting electrically driven pumps in each square mile, has been proposed by engineers who know the local conditions of a valuable tract of Northern India.

CHAPTER III

RESERVOIRS

THERE are two main sources from which water supplies for irrigation or domestic consumption are obtained : (1) Surface Supplies directly from lakes and rivers or by impounding rivers and streams, and (2) Underground Supplies from wells and borings.

In the case of surface supplies which necessitates the building of a dam to impound the water, the question of a suitable reservoir site is one of considerable importance ; the object being, as far as is practicable, to hold up the desired volume of water by as cheap a dam as possible. The shape of the valley, size of catchment area and amount of run-off rainfall are the factors which lead the engineer to his final selection. The chief geological consideration is that the reservoir bed should be water-tight.

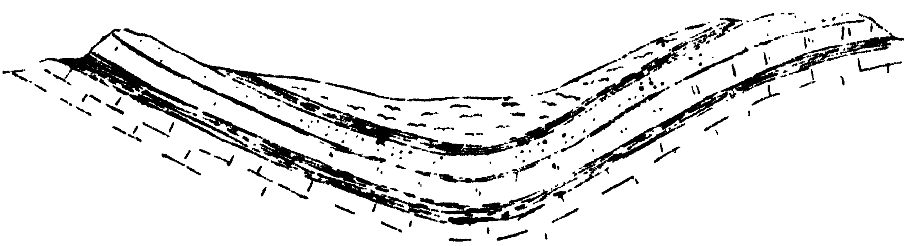


FIG. 3.

Section of structural valley of the trough type.

The Structure of Valleys.—The perfect reservoir site would be in a deep basin-shaped valley situated on impervious rocks, and having an out-fall through a narrow gorge. If the underlying and surrounding rocks of the valley consisted of sheets, or beds, of clay rock which were also bent into the shape of a true basin, the geological considerations would also be ideal. Such structural valleys, as these types are called, are exceedingly rare, and it is unlikely that the engineer will find one in the locality where the impounded water is to be stored. There are two types of valleys, from the geological point of view. These are known, respectively, as Structural valleys and Erosion valleys.

Structural Valleys.—When a valley lies in a trough, or synclinal fold, of bent strata (Fig. 3 shows such a case in section),

or when a valley is coincident with the line of a rift or fault (Fig. 4 shows an example of this, also in section), the valley belongs to the structural type. Examples of both these kinds of structural valleys are occasionally met with, though they are not common. The Thames valley—particularly the lower reaches of the river from near Windsor—lies in a trough of strata. The Jordan valley is an example of the fault type. A great fault, which lets down the strata to the east, traverses Palestine from north of the lake of Galilee through the Dead Sea to the Gulf of Akabar.

Sometimes valleys occur in depressions which are caused by the synclinal fold, or trough, crossing the direction of drainage at right angles. In such cases the corresponding arch of the fold may be seen in section on the sides of the valley lower down. Possibly the stream will have cut a gorge through this arch, or anticlinal fold, of the strata. Occasionally a cross fault, which

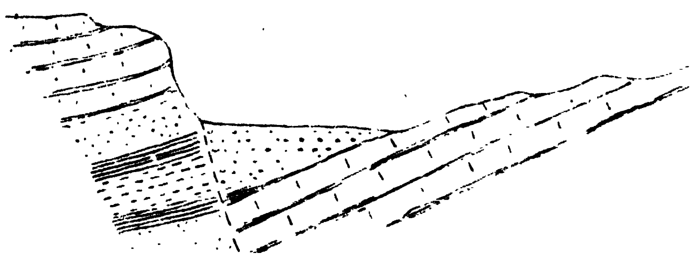


Fig. 4.
Section of a structural valley of the faulted type.

lets down the strata on the up-stream side, will cause a fine valley with an out-fall through a gorge.

If the hill-sides are not too thickly wooded, there should be little difficulty in observing the dip of the strata in the *unfaulted* types of structural valleys. An examination of the exposed beds should also reveal the presence of porous strata and the possibility of their presence in the valley floor.

If the axis of a trough, or synclinal fold, is not horizontal, but tilted downwards towards the up-stream side of the valley, it may be structurally to the advantage of a reservoir site. On the other hand, serious leakages may take place if the axis of the trough, or synclinal fold, is tilted down-stream at a greater angle than the gradient of the valley floor. (See Fig. 5, which shows this case both in cross and longitudinal section).

In structural valleys of the faulted type with the fault parallel to the valley, there is usually a considerable leakage from the stream to the plane of the fault. The detection of a fault of

this type should not be difficult, if the succession of beds on each side of the valley are carefully compared. The slopes on each side of a valley are seldom the same—those on the downward side of the fault, if dips are towards the valley, are usually less steep. This difference of slope on each side of a valley is often the result of tilted, conformable strata, the beds of which strike parallel to the valley, so that proof of a fault should be established and not presumed.

A cross fault—one at right angles to the valley—may be an advantage. This is generally the case if the strata dip up-stream and abut, on the down-stream side, against impervious beds. Cross-faulting, with the down-throw on the down-stream side generally results in waterfalls in the stream. Some of the cataracts on the Nile are said to have this structure.

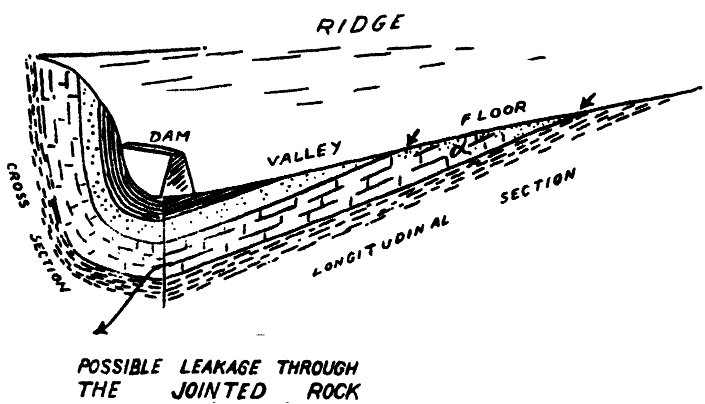


FIG. 5.

Section showing axis of trough of structural valley more steeply inclined down-stream than valley floor.

The question of finally deciding in favour of, or against, a proposed reservoir site in any of the various kinds of structural valleys above described, will usually depend on the suitability of the location on which the dam is to be built.

Erosion Valleys.—Erosion valleys are the commonest type with which the engineer will have to deal. The Grand Canyon of Colorado is perhaps the most typical example of an erosion valley. It has been carved out of soft, almost flat-bedded rocks by the sheer erosive power of the river. Less striking examples occur in many countries. In western India, there are erosion valleys, over 2,000 feet deep, which have been carved out of bedded sheets of hard basalt. Erosion valleys are not always associated with a simple geological structure. In mountainous country, where the ranges represent true orographic features,

the valleys are frequently found to lie in carved-out, anticlinal folds (see Fig. 6), while the ridges generally overlie synclinal folds (as shown in the same section of Fig. 6). The explanation of this is simple. The outer portion of an arched fold normally breaks under the tension of the bending; thus the strata on the arch will be more liable to erosion than the normal rock. On

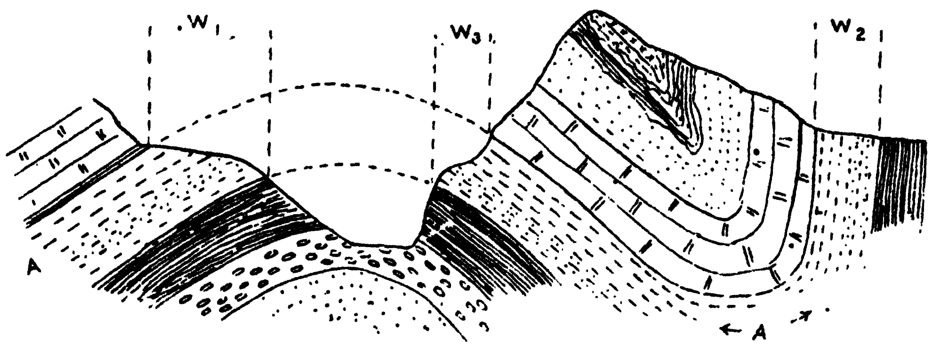


FIG. 6.
Typical erosion valley and corresponding ridge in mountainous country.

the other hand, the rocks in the inner portion of a trough fold will will be tightly compressed by the bending, and the strata in the trough will, therefore, be less easily eroded. In some cases, more complicated structures are met with (see Figs. 7 and 8, in which corrugated strata are shown bent into a synclinorium and anticlinorium respectively).

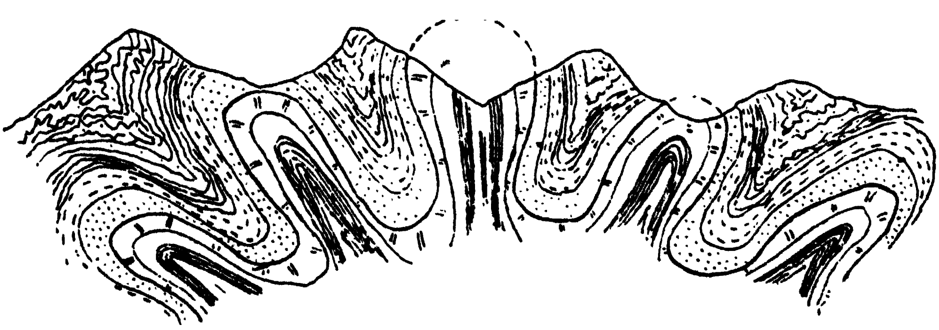


FIG. 7.
Section of an anticlinorium. Note valleys in the arches of the folded strata.

Reservoir sites in any type of valley require careful examination. In the case of erosion valleys in folded rocks, the examination has to be minute. Porous strata may occur in the banks, or floor, of the reservoir. Rocks, which are normally impervious, may have become porous owing to their fractured condition.

Factors which Govern Water-tightness.—Thick deposits of alluvial clay on the floor of a reservoir site often produce a water-tight bed, although the texture and structural features of the underlying strata are unsatisfactory. It may happen that a valley with a perfect basin structure is utterly useless, because the beds forming the basin are open-textured, and therefore porous. Cases are known where, though the floor of a valley is composed of porous rocks, there is an underlying stratum of impervious shale or clay, which completely secures the water-tightness of the valley. It is not in examples such as these, where the structural features are obvious, that danger is to be apprehended. Defects are, usually, easily detected in these cases. Trouble is more frequently encountered with small patches of porous rock, or from insignificant, irregular cracks in the bed

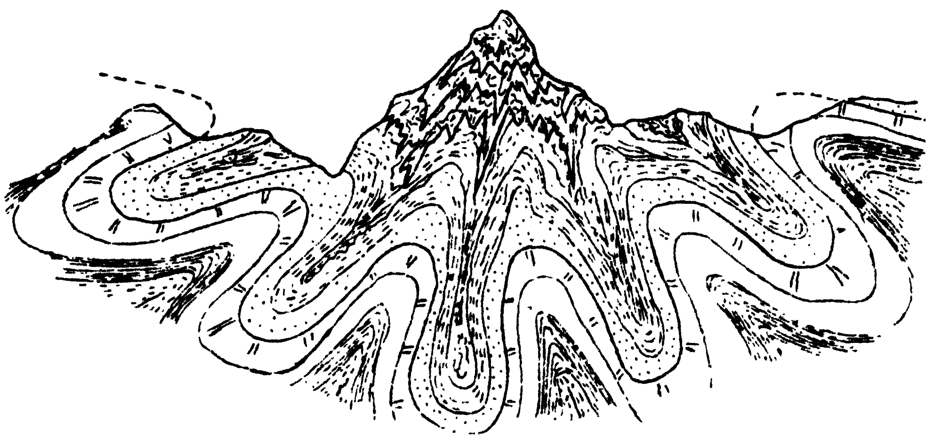


FIG. 8.

Section of a synclinorium. Shows peak of metamorphosed rock in the trough of the great fold.

of a reservoir. These fissures may connect downwards with porous beds or heavily jointed strata which are not seen. The utmost care is, therefore, necessary in choosing reservoir sites—especially for deep reservoirs or those from which losses can ill be spared. Almost every square foot of an important reservoir bed should be examined, and numerous pits made, to test whether the water-covered portion will be water-tight.

Clays and shales are generally impervious. All very hard, fine-textured rocks, though impervious in themselves, are usually jointed. This may result in greater leakage losses than the seepage from a porous-textured, unfissured rock. Nearly all igneous rocks become porous when they are decomposed. The unaltered varieties, on the other hand, are seldom free from joints. In the fine texture types, e.g. basalt, the joints are generally close

together. Coarse-textured masses, like granite, have fewer but larger joints. Undecomposed, metamorphic rocks, e.g. banded gneisses and schists, are impervious to percolating water in a direction at right angles to their foliation ; percolation may, however, take place along the planes of foliation. Buckled and folded varieties of all hard rocks are liable to contain joints, or fissures, or cleavage cracks. Massive, hard limestones are seldom without strong joints, and, being soluble in certain kinds of infiltrating water, the channels of percolation tend to become larger. If, added to this, there is the pressure of the "head" of water in the reservoir, it is evident that in time the leakage will be enormous.

Catchment Areas.—The nature of the rocks which are exposed within the limits of the drainage, or catchment area, of a stream, influence the amount of run-off and percolation which a given rainfall will produce. If the exposed rocks of an area are porous, the run-off proportion of the rainfall will be small, while the amount which sinks into the ground will be comparatively large. In the case of an out-crop of inter-bedded, porous and impervious strata, percolation will only take place in the out-crops of the porous beds. The porous beds may be vertical or inclined or they may dip in any direction in the valley. The water which percolates into the out-crop of such beds in the drainage area of one river system may re-emerge as springs, and contribute to the drainage system of another river. In many cases, the water will not re-emerge at all ; it will percolate down, either to the standing water in the porous bed, or into the standing water of a complex underground water system. The term catchment area, therefore, may apply to surface drainage as well as to underground percolation. In the same way as slope of ground and vegetation effect the run-off of a surface catchment area, so the porosity of the rocks effects the rate of percolation from a porous out-crop. The extent of the area on which rain falls and the total rate of rainfall precipitation naturally influence the quantity of water which a given out-crop (catchment area) may obtain by percolation for an underground water system.

CHAPTER IV

INFILTRATION CHANNELS AND WELLS

In most countries, large quantities of water are obtained from wells—particularly in villages and out-lying places. The majority of wells for domestic water-supply seldom exceed a depth of 60 feet. In some districts, it is necessary to sink to deeper depths. Some factories obtain water from wells 200 to 300 feet deep. When the ground water is known to lie at depths greater than 200 feet, especially below hard rock, it is usual to put down borings. In rare cases these borings attain a depth of 2,000 feet.

Wells for domestic supplies are frequently found in the vicinity of stream courses, the wells evidently tapping the underground percolation which is associated with the stream flow, and which, as previously stated, must continue for a considerable period after the stream itself has run dry. In regions in which little is known regarding the underground water, it would, therefore, be better to locate wells at the junction of stream courses than anywhere else, unless local knowledge gave reasons for other sites.

Alluvial Deposits.—There are many factors which complicate the problems of water-supply from wells. The most important of these is the texture and geological structure of the rocks which occur in a given locality. It is well known that the larger the diameter of a well which is sunk in porous ground below the ground-water level, the larger the amount of water which will enter the well in a given time and consequently the greater the capacity of the well. In some cases, deep trenches or infiltration channels, cut in alluvial water-bearing ground, have, for some periods, proved of enormous value in relieving the distress caused by water-shortage.

Deposits of gravel and sand, which are occasionally found as an apron or fringe to a range of hills, frequently contain excellent supplies of water in an otherwise waterless region. In Baluchistan this type of debris is locally called *dhaman*, and elaborate methods are employed for tapping the contained water. Low-gradient channels are cut and then continued as tunnels, sometimes for as much as a mile, into the debris. The gradient of the floor of

these drivages is, of course, outward, so that when the ground water is tapped a steady flow emerges from the cutting.

Abundant supplies of water are often to be obtained by wells or filter cribs from the sands in the apparently dry beds of large streams (see Fig. 9). In some cases, where the subsoil and underground water of an alluvial tract are impregnated with saline matter (usually chloride and sulphate of soda), shallow wells in the dry stream bed may be the only sources of "sweet" water-supply in a wide tract of country. If these wells are sunk too deep, they will pass through the zone from which the salts have been leached by the underground flow of the stream, and tap saline water (Fig. 2, which represents a section across the river bed of such an area, illustrates the point.) Reference has previously been made to the danger of diverting the flood flow of streams in regions where these conditions exist.

Town Wells.—In a large number of cases, wells are sunk on high ground and are dependent on the direct percolation of the rainfall. Under these conditions, each well requires a fair-sized area of ground or catchment, for its infiltrating water. While the houses are spaced at sufficient distances from each other, the wells in each garden can usually supply the requirements of the occupants. If new houses are built between the older houses and more roads (with impervious surfaces) are constructed in the same area, it is evident that the catchment areas of the original wells may be seriously decreased. If, in addition, fresh wells are sunk within the catchment areas of the older wells, it is quite likely that the capacity of these wells will be diminished. Various expedients, such as driving short tunnels and cross drifts from the bottom of the wells or by greatly deepening the wells, may improve matters and meet the requirements of the several houses concerned. If the congestion of houses and the making of roads are continued, as will be the case in a growing town, such sources of water-supply may eventually prove unsatisfactory as well as unsanitary.

Wells in Igneous Rocks.—Granites and basaltic rocks constitute two of the main varieties of the igneous rocks which are met with on an extensive scale. Other types of igneous rocks occur in some places, but the remarks made with regard to granites and basalt will generally be applicable to the other cases. The texture of unaltered igneous rocks is, as a rule, non-porous. The several mineral components which make up the rock are closely interlocked. Consequently, the prospect of obtaining water from wells sunk in these rocks would be useless, if it were not for the joints and fissures which traverse igneous rocks. Great irregularities of the underground water-level occur in such material.

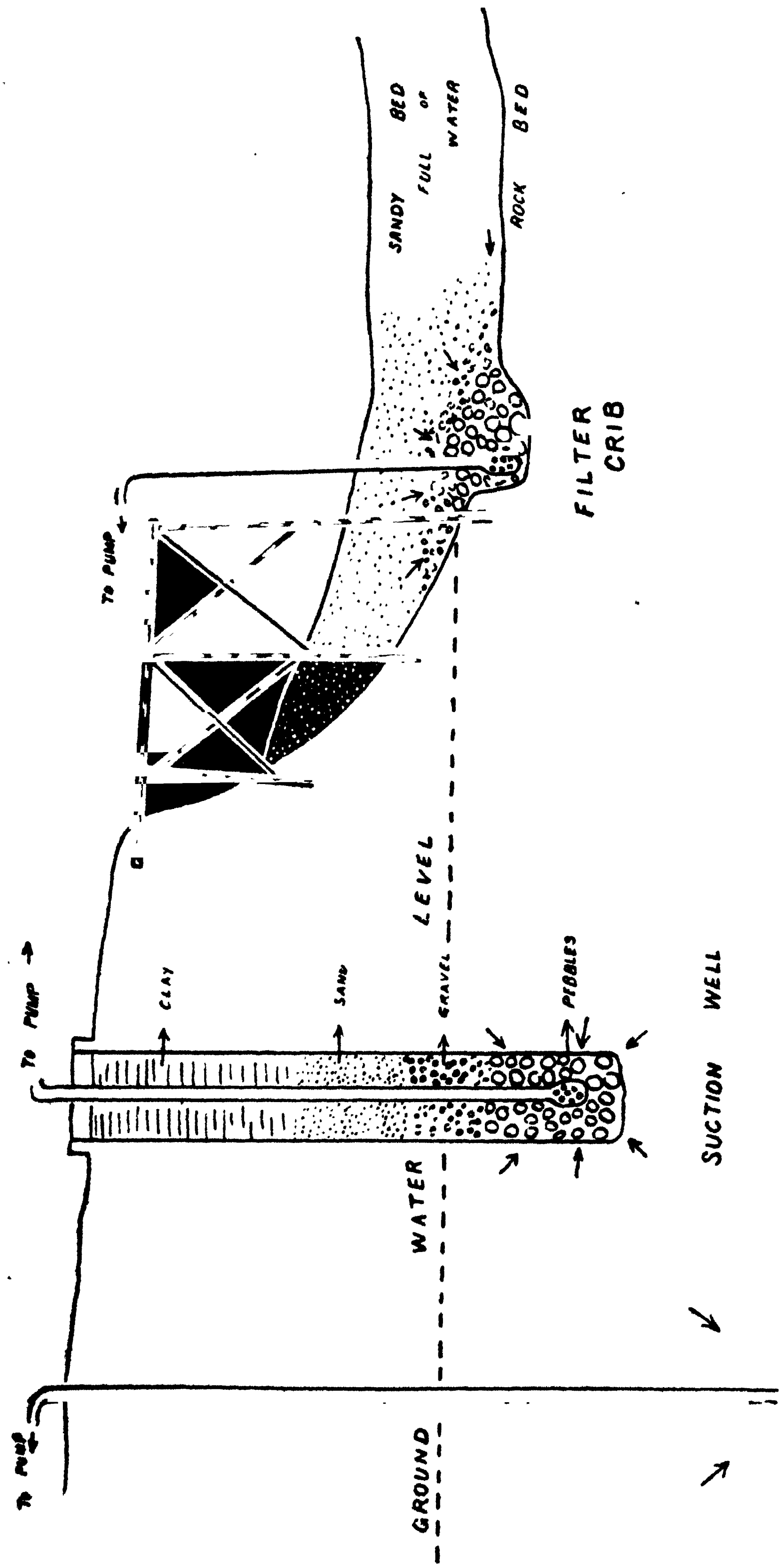

TO PUMP
TUBE WELL
GROUND WATER LEVEL
TO PUMP
CLAY
SAND
GRAVEL
PEBBLES
SUCTION WELL
TO PUMP
FILTER CRIB
SANDY BED FULL OF WATER
ROCK BED

Fig. 9.

In one place a well might strike a big fissure and produce enormous quantities of water. In another area, in an endeavour to increase the capacity of a moderate well, by deepening the well a strong joint may be encountered which will possibly drain the well. It is true that by going sufficiently deep these losses can be averted, but the rocks are hard and sinking costs money. Granitic rocks constitute a most difficult problem if the great joints cannot be located and the rock is hard and compact. Decomposed granite is, however, porous, and if well sites are chosen in low ground on, or near, lines of surface drainage, success may attend the results of sinking a well. So much depends on local conditions, i.e. other wells in the vicinity, the configuration of the ground, etc., that it is impossible to say what should, or should not, be done in a particular case. Basaltic rocks, on the other hand, are more heavily jointed, and, if covering large areas of country, they will generally be as beds of lava—perhaps 30 to 100 feet thick. The separate sheets of lava are normally separated by beds of impervious clay. In rare cases porous strata may be intercalated. The water in the basalt layers will invariably lie or percolate along the numerous joints which traverse these rocks. The upper part of each lava stratum is generally decomposed and porous, and should therefore contain most water. In these rocks, if insufficient water has been encountered, it is wise to continue sinking and terminate the wells in the upper part of an underlying lava flow. Coarse-textured basalts, or dolerites, are sometimes met with, and in these the conditions become more like those of granite areas. In the majority of cases, except for granite and sheets of basaltic lava, igneous rocks do not occupy large surface areas. They rather constitute irregular zones or belts in sedimentary or metamorphic rocks.

Wells in Sedimentary Rocks.—The most familiar types of sedimentary rocks are various kinds of sandstones, shales and limestones. Coarse, open-textured sandstones are usually good storage reservoirs for underground water—provided the topographical and structural conditions are suitable. Wells in shales are usually failures. Very rarely some hard, slatey shales are fissured sufficiently for the percolation of water through them. Thinly bedded limestones are also very unreliable sources for water. In the case of massive limestones, if the structural and topographical conditions are suitable, great subterranean channels and pockets full of water may sometimes be met with. Cavities of this kind are caused by the solvent action of the percolating water in its passage through fissures in the limestone. These sources of supply are subject to sudden cessation, particularly after earthquakes, owing to the softness of the rock and the collapse of these subterranean caverns and channels.

Sandstones are perhaps the most important of the sedimentary beds in questions of water-supply. They, however, vary in texture and porosity. Coarse, soft-textured types allow easy percolation and hold large quantities of water in the interstitial spaces between the mineral grains. Fine-grained varieties do not permit so free a percolation as the coarse types of sandstone. In many sandstones the pore spaces have become choked with precipitated lime or iron oxide or silica, and the rock has been rendered impervious.

The regularity of the bedded structure of sedimentary rocks, especially when the strata have been folded or tilted to occupy inclined positions, is sometimes not appreciated. Instances have occurred in which wells have been abandoned within a few feet of success when the depth could have been calculated. The out-crop of a certain porous horizon often shows the dip of the bed very clearly, and with this information the depth of the well can be calculated. If care has been exercised in determining the correct dip, the completed well is frequently successful in tapping the water-bearing zone at or very near the calculated depth.

Wells in Metamorphic Rocks.—Gneisses and schists are typical examples of metamorphic rocks. Other varieties are schistose slates or phyllites, quartzites and crystalline limestones or marbles. The predominant features of these rocks are their general impervious texture, banded occurrence and generally twisted and buckled structure. Unless severely fractured and jointed, they are the poor sources from which to obtain well water. Some weak percolation may take place along the foliation planes if the rocks are somewhat weathered or decomposed. The less metamorphosed types, i.e. the quartzites, slates and marbles, are usually jointed, and therefore may contain water in the joint planes. The question of obtaining water in massive quartzites, traversed by strong joints, is somewhat similar to that of obtaining water in granite country. The case of crystalline limestone is also similar to that of granite, although there will be more likelihood of obtaining water from the marble than from the massive quartzites.

The metamorphic rocks by their texture resemble the igneous rocks, and in their banded structure resemble the sedimentary rocks. Consequently they suffer from the water difficulties of both. The gneisses and schists are particularly discouraging. The rate of infiltration even from weathered gneisses is generally slow. Wells, in these rocks, if heavily drawn upon, take a considerable time to refill. Although tunnels are sometimes driven across the banding of these rocks from the bottom of such wells, their capacity is seldom largely increased.

CHAPTER V

ARTESIAN CONDITIONS

THERE is perhaps no simpler geological structure nor one so seldom understood by the ordinary layman than that designated by the word artesian. It conjures up pictures of spouting fountains and flowing ditches and a cessation of water troubles.

When a porous bed of rock occurs inter-stratified between two impervious layers of rock and all three beds are folded to the shape of a basin or a trough, the structural conditions are suitable for an artesian well (see Fig. 10). If the porous bed is thick and exposed in a wide out-crop (a large catchment area), it may contain large quantities of water—particularly if the size

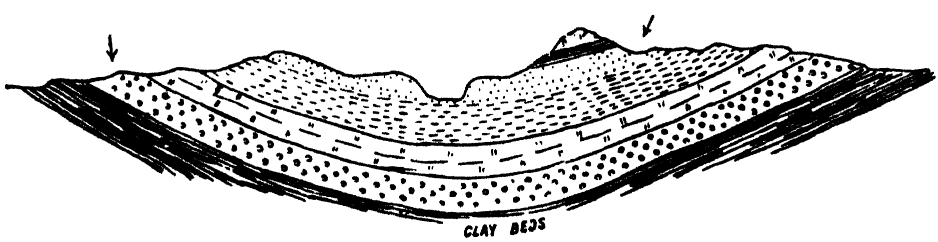


FIG. 10.

Geological structure favourable to obtaining water under artesian conditions.

of the trough or basin is large. The question as to whether the water will flow out of a bore-hole, which is put down to the porous bed in the deepest portion of its sag, is one which depends on the relative heights or levels of the out-crop of the porous beds and the ground surface at the top of the borehole (see Fig. 11). If the out-crop or catchment area of the porous bed is at a higher level than the top of the bore-hole, water may flow from the bore-hole when the porous stratum is tapped. On the other hand, if the top of the bore-hole is at a higher level than the out-crop of the porous bed, it is obvious that the water, although it may rise to a considerable height in the bore-hole, cannot exceed the level of its intake, i.e. the lowest point of the out-crop of the porous bed. In this case the water will have

to be pumped out of the well. In the former case the boring produced a flowing well. In both cases artesian conditions exist.

There are numerous examples in which imprisoned waters are found under hydrostatic pressure. These artesian conditions show (1) the presence of channels for the infiltrating water, (2) the intercalation of these channels between impervious layers of rock, (3) a difference of level between the place where the water enters the channels and the point at which the imprisoned water is tapped by a boring. These conditions are shown in Fig. 11. In this example, when the water-bearing stratum is full of water, any additional infiltration will cause springs to occur at C. In the case represented by Fig. 12, the fault plane functions as a channel for percolation in conjunction with the porous bed.

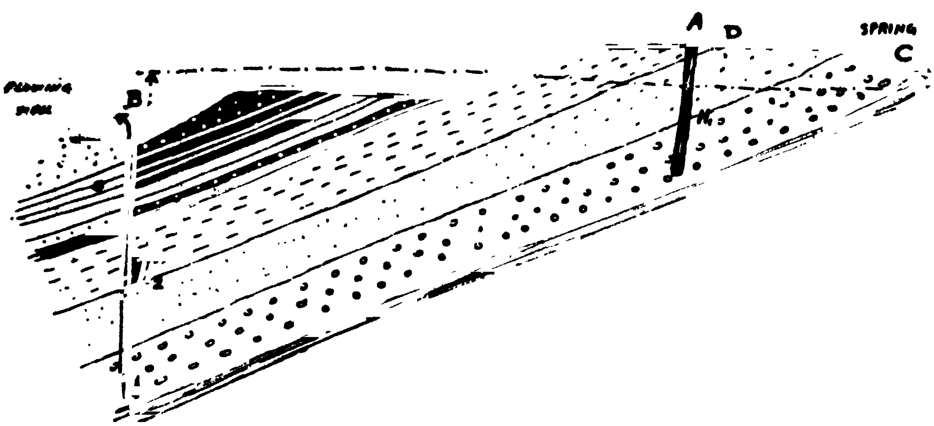


Fig. 11.

A, top of non-flowing well (level above C).
B, top of flowing well (level below C).
D to C = out-crop of porous beds.

The bore-hole completes the U-tube structure. Consequently the water will rise in the bore-hole as far as the hydrostatic pressure permits. The quantity of water will depend on the capacity of the well. If large volumes of water are available in the inter-spaces of the sandstone and there is little "loss of head" (due to resistance to the flow of water through the sandstone), considerable quantities may be obtained from the well. If the well is of the flowing type, the first discharge of water may be more than will be subsequently maintained. When the well finally adjusts itself, so that the out-flow from the well is governed by the percolation to the well, the rate of flow may not be sufficient for the requirements of the day. In such cases a pump is attached, and the well over-pumped in the day and

allowed to recover during the night. The total quantity being the same in each case. It is generally preferable to pump rather than store the slow discharge. By pumping, a certain amount of suction is produced, and the infiltrating channels may be improved. In fact, the action of the tube well is introduced (see Fig. 9). In some cases two parallel faults, which let down a strip of country into a trough—like the Great Rift Valley which traverses Nyassaland—may produce excellent artesian conditions. The faults, in such cases, may function as infiltration channels to an underlying bed of porous rock. In other instances, particularly in the so-called crystalline (granitic) rocks, the strong joint planes may function as the channels for infiltration, and very large supplies of water, under pressure, may occasionally be obtained from such sources, in some places. A boring may

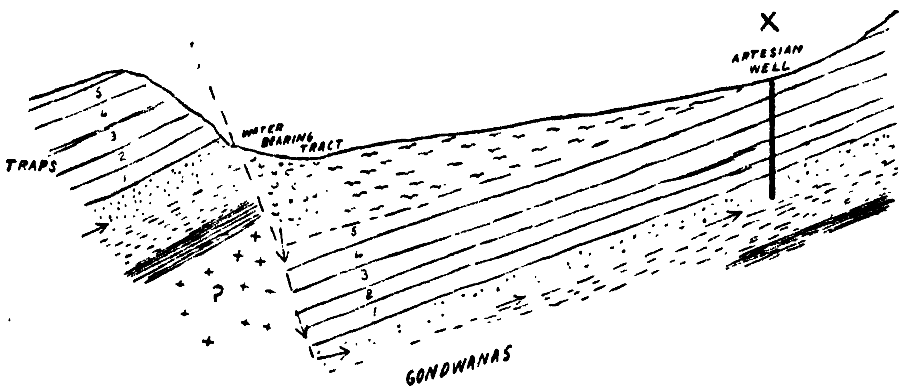


FIG. 12.

Artesian conditions due to a fault. The boring at X will *not* produce a flowing well.

tap a large cavern in an underlying limestone and, if this cavity is full of water under pressure, thereby obtain enormous quantities of water under artesian conditions. In such examples as have been given and in various others, it is clear that the geological structure of the underlying rocks must be correctly determined and equally important, the presence of an interbedded porous bed, or other water-holding zone, be ascertained. The porous bed is the crux of the whole question; without it there can be no water, however perfect the structural features of the strata.

The total volume of pore-spaces in a rock is a guide to the porosity of the rock, but does not give its water-bearing capacity in actual practice. For example, the percentage of

the pore-space volume, of various rocks may be, roughly, as follows :—

	Per cent.
Soil and loam	50
Clay (ordinary dry)	40 to 50
Chalk (soft)	40 to 50
Sand (firm)	30
Sandstone (soft)	20
Sandstone (hard)	10
Slate and shale	3 to 5
Limestone and marble	2 to 4
Granite (unaltered)	up to 1
Quartzite (fine, hard)	below 0·5

Figures of this description are generally only useful for guidance in the choice of building stones, which are used in comparatively small sized blocks. They are, however, quite useless in questions of water-supply. The pore-spaces of clays are too small and do not allow of the *passage* of water. The granites may be practically non-porous, but they are always traversed by joints, and it is from these that the underground water, in a granite country, is obtained.

PART II

Field Operations

CHAPTER I

RETAINING WALLS

WALLS which are built to impound water are known as dams, whereas those which are constructed to retain loose materials, rock debris, etc., are usually called revetments.

Dams.—In designing a dam, the engineer always determines the amount and direction of the thrust on the foundations of the dam. This force is the resultant of the push of the water and the weight of the dam itself. The materials utilised and the method of construction of a dam should be such that the dam will safely keep these forces in equilibrium. Much, however, depends on the choice of the site for the foundations of the dam. The underlying rock must be strong enough to take the weight of the dam and withstand the resultant thrust. In addition, these rocks must be sufficiently impervious in texture and free from open fissures to prevent serious leakage of the impounded water. If this water gets under the dam with sufficient hydrostatic pressure, the upward component of this force will partly counteract the weight of the dam and thereby add to the danger of the dam being rolled over by the horizontal push of the impounded water.

The most suitable site for a dam is on a strong, massive band of impervious rock. Granite free from joints and fissures would make an excellent foundation for any dam. Such locations are not common in actual practice. In most instances, valleys are carved out along the lamination of the strata; consequently, the strike of the beds will be at right angles to the length of the dam. When a river breaks across a ridge by cutting a deep gorge at right angles to the strike of bedded or foliated rocks, an ideal dam site may be found in the gorge. Generally, however, dams have to be built in shallow valleys on rocks which are seldom absolutely satisfactory. Much is left to the skill of the engineer to make the foundations good.

Dams on Unconsolidated Rocks.—Dams intended to hold up a great depth of water cannot be efficiently founded on soft or porous, unconsolidated strata, such as sand or loam, or clay. In the former case, the loss by percolation would be considerable, and the dam might be destroyed by overturning; high dams

built on clay would be pushed along their foundations and bulge and most probably collapse. It is to the credit of the engineer that records of such failures are exceedingly few. Although it is dangerous to build high dams (above 75 feet) on loose material, and unwise to risk dams of moderate height (30 to 75 feet) on such foundations, it is possible to construct efficient low-pressure dams on such ground, provided there are no open cracks or fissures in these foundations. If the underlying material is clay, there should be no difficulty in testing for interbedded, porous beds, and, if these are not present, the building of a thoroughly reliable water-tight dam should be practicable. In the event of the underlying material being a bed of sand, the conditions are entirely different.

Professor Boyd Dawkins (see James Forrest Lecture, " On the Relation of Geology to Engineering," *Min. Pro. Civil Engineers*, vol. cxxxiv. 1898, p. 254) called attention to discoveries made by that great engineer Robert Stephenson in connection with the flow of water through sands. In driving the Kilsby tunnel, near Rugby, beds of water-logged sands were encountered, and it was first thought that the whole of these sands would have to be de-watered by pumping before satisfactory progress could be made. Stephenson, however, soon discovered that, owing to the resistance which the water encountered in its passage through the sands to the pumps, the water-surface occupied an inclined position. By pumping on the precise level of the tunnel alignment, a dry valley in the water-surface of the sands was made and the work of construction continued without de-watering the whole of the sand.

W. R. Baldwin-Wiseman has experimentally determined the influence of pressure and porosity on the motion of sub-surface water (see *Quart. Journ. Geol. Soc.*, vol. 63, 1907, p. 80, etc.). He found that the rate of flow of water (D) through filter-beds varied with the thickness of the sand (L), the pressure of the water (H) and the size of the sand grains (G).

(1) When H/L = 5 and sand under 60 mesh.

H in feet.	L in feet.	D cubic feet per hour per square foot of sand.
1·25	0·25	11·6
21·25	4·25	2·7

(2) When H/L = 2.

	G = under 60 mesh	on 50	on 40	on 30	on 20	on 10	on 6
D was ..	1·8	4·2	7·0	12·3	21·7	35·4	43·2

(3) When H/L = 1.

	G = under 60 mesh	on 50	on 40	on 30	on 20	on 10	on 6
D was ..	1·4	3·2	4·9	9·2	15·1	30·4	37·2

A low dam of great width, if built of impervious materials and water-tight in itself, would, by its weight, compress the sand under its foundations and decrease the size of the interstitial spaces between the grains. The leakage from the reservoir would therefore be reduced, owing to the increased interstitial friction of the sand. With small depths of water in the reservoir, and careful building of the dam, the loss by leakage would be far less than might be anticipated.

The building of dams under these conditions is, however, seldom warranted. If the thickness of the sand is less than 12 to 15 feet, it may prove cheaper to build a normal dam with its foundations on the underlying rock than to construct an abnormally wide dam. On the other hand, if the thickness of the sand is considerable (above 30 to 40 feet), no dam may be necessary, as abundant supplies of water will probably be obtainable by pumping from filter cribs in the sand.

The weight of structures on foundations of various kinds of rock are, normally, limited to the following amounts for safe work :—

1. Soft clay and loam carry 1 ton per square foot.
2. Ordinary clay or dry sand mixed with clay carries 2 tons per square foot.
3. Dry sand and hard, dry clay carry 3 tons per square foot.
4. Rammed, dry clay and firm, coarse sand carry 4 tons per square foot.
5. Firm, coarse sand or gravel carries 5 tons per square foot.
6. Hard shale carries 8 tons per square foot.
7. Common brickwork carries 12 tons per square foot.
8. Sandstone masonry carries 20 tons per square foot.
9. Hard limestone masonry carries 25 tons per square foot.
10. Granite masonry carries 30 tons per square foot.

Thus it is seen that although the soft clay will support a column of 36 feet of water (pressure of which is, roughly, 1 ton per square foot), it will not support the weight of a dam 36 feet high unless enormously wide foundations are made to carry a relatively slender-sectioned dam. According to these figures, there should be no difficulty in supporting 36 feet of water by a dam on sand foundations, provided the thrust on the foundations is safely held.

Dams on Solid Rock.—Massive rock such as granites, dolerites or other igneous types. and gneisses and schists, quartzites, hard limestones and even fine-textured sandstones, if free from open joints and fissures, make excellent foundations for dams (see cross-section in Fig. 5). In porous rocks such as open-textured sandstones, decomposed granite or dolerite, etc., and

the peculiar substance known as laterite, there will be considerable percolation if there is a great depth of water at the dam.

Interstitial percolation does not necessarily lead to serious leakage losses if obviously porous rock is avoided. By far the most serious defects in the massive rocks are the open cracks and joints which are so repeatedly met with in cutting foundations in these rocks. Such fissures discharge enormous volumes of water when the sluice gates are closed and water impounded. In limestones, the solvent action of the water steadily enlarges the channels of escape, until these may become so large that they collapse, and the subsidence which takes place may destroy the dam. In the majority of cases, these fissures are of small dimensions and do not extend far into the rock; consequently it is possible to trace their ramifications and seal them up with cement grouting. The joint planes of massive rocks, e.g. granite, on the other hand, usually have deeper connections, which may prove difficult to render water-tight. The most troublesome kind of fissure is that due to faulting—particularly if it crosses the length of a dam obliquely—because it may be impossible, at reasonable cost, to seal against leakage of water from a reservoir. Further, the strata on opposite sides of a fault-plane are always liable to displacement during earthquakes, and such movement would, besides re-opening the fault-fissure, involve the rupture of the dam. It is hardly necessary to add that no important dam should be built across a fault-plane, even in regions free from earthquakes. Dams should be built on the up-stream side of a fault which crosses a valley parallel to the length of the proposed dam.

Flood-dams.—In the case of flood-dams there is less need for care, because the impounded water is rapidly discharged. The danger that may be anticipated in such cases arises from the fact that many flood-dams hold up a permanent volume of water, and this, by percolating for example into faulted limestone, may lead to the collapse of the dam, or by infiltrating into the workings of important mines result in flooding them.

Dams on Bedded Rocks.—A large number of dams are built on bedded or laminated or foliated rocks. The planes of bedding or foliation may be parallel to or across the length of the dam. They may be inclined at any angle, or they may be buckled into close folds. The individual beds of the strata may consist of porous rock intercalated with impervious layers. Each site requires careful examination. Figs. 13 and 14 show cross-sections of typical erosion valleys in mountainous country. In each case the valley follows the axis of an anticlinal fold. In Fig. 13 the bed and banks of the stream in the valley consist of marls

which are overlaid by porous sandstones. A dam built in this valley will be water-tight up to the height of the marls; above that level leakage will take place, through the sandstone, round the abutments of the dam. In Fig. 14 a bed of sandstone is exposed in the bed of the stream. It is bent in an arched fold and is almost certain to be heavily fractured. The work of building

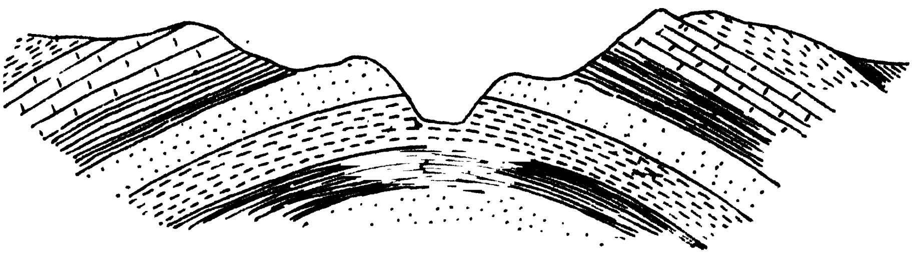
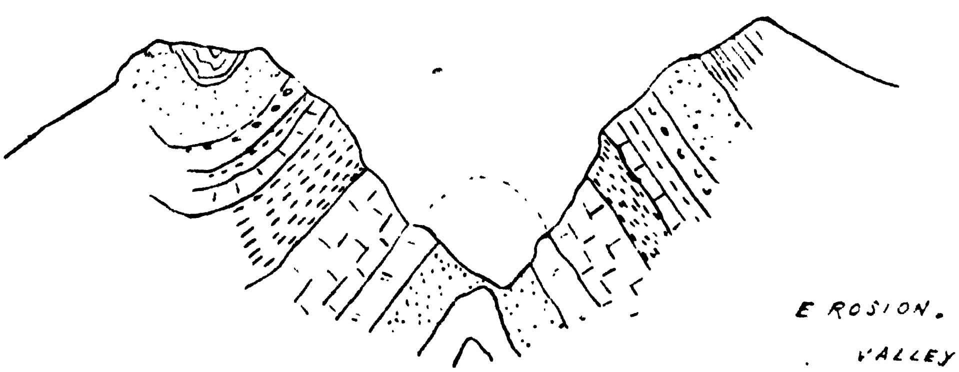


FIG. 13.
Impervious beds in the valley floor. Porous bed shown on the banks.

the dam will prove costly, as it will be necessary to make the foundations of such a site water-tight. If the sandstone is exposed in the upper bed of the stream for any distance, the whole project may have to be abandoned. It would be practically impossible to prevent leakage without enormous expense, unless the valley was deeply covered with stiff clay or silt.

Dams Parallel to Strike of Rocks.—Among the bedded



14.
Porous strata exposed in river bed.

rocks it is obvious that the length of a dam should, if possible, be cited parallel to the strike of the bedding, and that the foundations be so laid as to have an apron of an impervious bed under the edge of the dam. If the beds strike parallel to the length of the dam and there is a choice of two sites, one with the beds dipping up-stream and the other with down-stream dips, it is generally

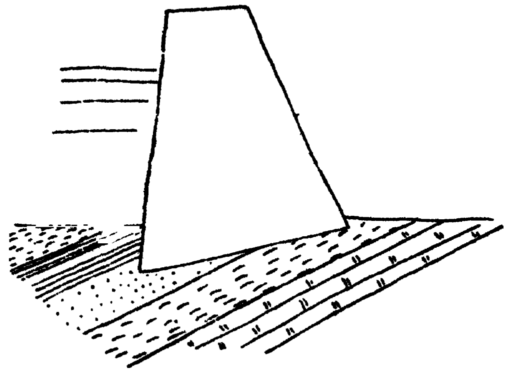


FIG. 15.

Dam shown on strata with up-stream dips. Note impervious bed, which has been utilised as an apron on the reservoir side.

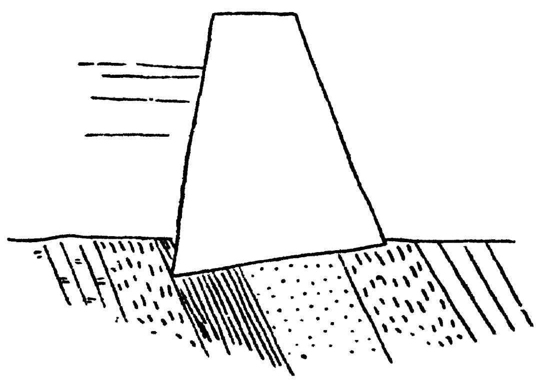


FIG. 16.

Dam located on strata with down-stream dips.

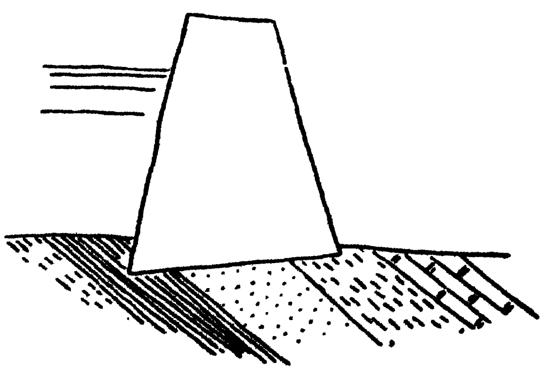


FIG. 17.

Dam on beds with down-stream dips.

preferable to locate the dam on rock with up-stream dips. In Fig. 15 an ideal cross-section of such a case is shown. The dam is represented as having an impervious bed as an apron on the up-stream side. The geological features of this section are

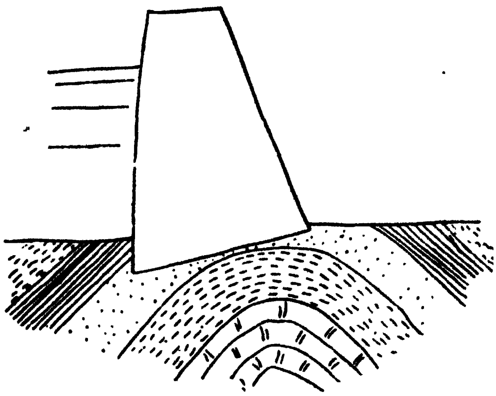


FIG. 18.

Dam located on an anticlinal fold of the strata. (Compare Fig. 15.)

excellent. Fig. 16 shows a dam situated on steeply inclined strata with down-stream dips. An imperious bed is depicted on the inner side of the dam. The structural features are good. Fig. 17 is a section of a dam on strata with low, down-stream

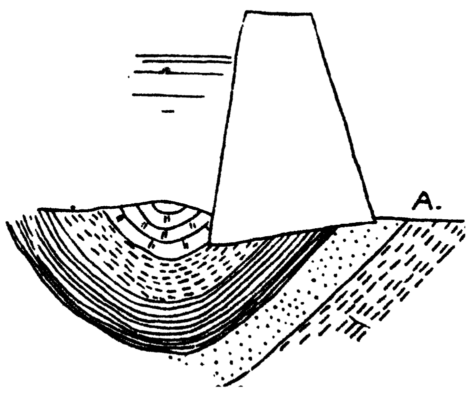


FIG. 19.

Dam situated on a synclinal fold of the beds. Location on down-stream side to obtain structure of Fig. 15.

dips. A bed of shale is shown on the inner side of the dam, while a band of sandstone supports the greater part of the weight of the dam. The site is good, although inferior to the two previous cases. Fig. 18 is a section of a dam on an anticlinal fold. In

this case the dam is built on the up-stream side of the fold so as to attain the ideal structure of Fig. 15. In the section represented by Fig. 19, the dam is shown on the down-stream side of the synclinal axis. There is a possible loss by percolation through the bed of sandstone which is exposed below the dam. If the dam were built somewhat lower down-stream, so as to expose the sandstone on the inner side, the site would be better chosen, because the percolation loss would be avoided and an apron of marl would be obtained.

Dams Built Oblique to the Strike.—If an engineer is compelled to build a dam across the strike of the rocks, he must locate his dam on the alignment which has fewest disadvantages and no serious defects. In such cases, the degree of dip, the number of possible percolation channels which cross the dam, the texture, and condition of the various bands, become very important factors in making a choice. Each disadvantage of strike, texture, etc., becomes magnified in proportion to the height of the dam and may assume the degree of a defect. No serious defects can be permitted in high-pressure dams.

When the dips of massive bedded or banded rocks are gentle and the strike of the beds is slightly oblique to the length of the dam, there may be few bedding planes through which water can find its way under the dam. On the other hand, if the rock is laminated and the beds vertical, with a strike transverse to the dam, there will be numerous planes along which water may percolate. If, in addition to these possible channels of infiltration, some of the beds are of a porous texture, it is evident that further leakage will take place. However, in ordinary storage dams, the porosity of fine-textured rocks, such as fine-grained sandstones and certain types of schist, should not be treated as a defect for which a dam site should be condemned ; and more especially is this true when the rock is free from open fissures. The most common cause of leakage from reservoirs is through open-joint planes and other fissures.

Materials used in Building Dams.—There are two portions of a dam which must be built absolutely water-tight. One is the floor or sole of the dam and the other is the face of the dam towards the impounded water. It is imperative that no water, under hydrostatic pressure, should enter the body of the dam. Loss by leakage is not the only factor involved in such cases ; a more important factor is that the weight of the dam is diminished by the upward component of the water pressure. This may cause the resultant thrust on the dam to become sufficiently tangential to overturn the dam.

In masonry or concrete dams which are backed with porous

materials, there may be an advantage in allowing this porous back to become wet by permitting water to soak into it from the top of the dam. In time, the water percolates down and thereby increases the weight of the dam and improves its stability.

The materials used in building and the rocks on which high-pressure dams are to be built require careful consideration. The underlying rock and the masonry of the foundations must be strong enough to bear the weight of the dam and the thrust which results when water is impounded. The crushing strength of the various types of rocks vary considerably (see table on page 124). It is generally difficult to cement the beds and joints of masonry in which great blocks are used. If these joints are

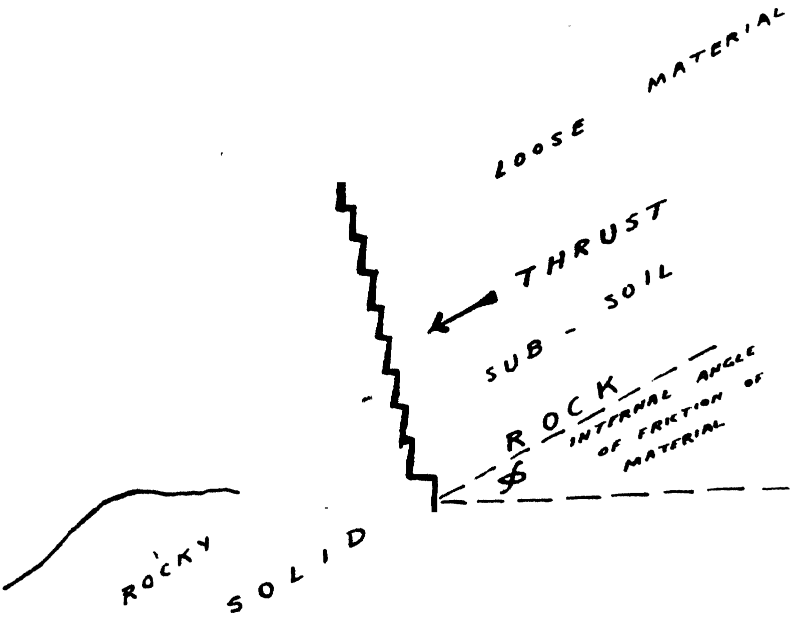


FIG. 20.

A surcharged revetment.

open, they will function as channels for escaping water. For this reason, it would seem advisable to build with moderate-sized blocks and ensure the water-tightness of the jointing. By so doing, the dam becomes similar in structure to a rock with cemented grains.

Revetments.—Retaining walls, such as dock walls and revetments, are usually built to hold up loose soil or rock debris. The so-called angles of repose of these materials are, in general, not steep enough to prevent a pressure or thrust on the retaining wall. It is not possible to calculate exactly what this pressure

may be, as much depends on the condition and nature of the material held up. The material supported by the revetment may be level with the top of the wall or it may be "surcharged" (see Fig. 20). In the latter case there will be a great thrust on the masonry or brickwork, in consequence of which the wall must be more strongly built. It is well known that the surface slope (angle of repose) of loose materials varies not only with the type, size and shape of the fragments or particles, but is very considerably affected by the degree of "wetness" of the material. For example, dry sand has a surface slope, or angle of repose, varying from 25° to 35°, while moist sand may stand for a time at 90° (i.e. with a vertical face); whereas, if sufficiently wet, the sand may be in equilibrium on a slope of 15°. This question is further discussed in the chapter on the "stability of hill-slopes," under the phenomenon known as "creep" (i.e. the gradual sliding movement of the soil and subsoil on slopes). In certain cases, surcharged revetments on hill-slopes have given way, not because they were not strong enough, but because their foundations were not built on solid rock. They were involved in the superficial "creep," and consequently moved down the slope under the influence of their own weight plus the thrust of the material behind them.

Quay Walls.—Under this title are included those retaining walls which, besides functioning as revetments, are built to be partly submerged by water. They are generally constructed with vertical or steep faces in order to utilise the full depth of a limited water-way, as in canals, docks, etc. Although they act as a containing barrier between opposite pushing forces—the weight of the water and the thrust of the supported material—they may, as in dry dock walls, be required to stand the push of the loose ground alone. If the wall is built of porous rock, the contained material will become wet and its thrust will be greater when the water in the dock or canal is lowered; also, while a porous wall is partly submerged, its weight will be reduced by the upward pressure of the water. This aspect of such walls lies outside the province of the geologist, except in so far as the choice of building material is concerned.

Erosion Walls.—This name is used comprehensively to include those types of walls which are made to prevent the erosion of a bank or shore by a river or the sea. These walls may be built with vertical or gently sloping faces, and either at right angles, as in groynes, or almost parallel, as in training walls, to the direction of the water-current.

A groyne with a vertical face towards the current offers an abrupt impediment to the scouring stream and may result in

severe undermining by the current at the head of the groyne. Such groynes, unless exceptionally well constructed, generally prove unsatisfactory. On the other hand, if the up-stream face of the groyne is at a gentle slope, it functions as an "expending beach," and may prove most efficient. Although training walls offer little impediment to the flow of a stream, they may, if built with a vertical face, be undermined by the scour of the current; consequently, the foundations must be carefully secured or the exposed face protected with an apron of stone or similar material.

Breakwaters.—These sea-walls are usually built as a protection for harbours against rough seas. In calm weather, they are subject to an equal push of water from each side, but their weight is reduced by the volume of water they displace. In heavy weather, the seaward face of the wall is exposed alternately to heavy blows, followed by the sucking action of the receding waves. If the breakwater opposes the full force of the waves with a vertical face, the incoming water-blow may be as great as 3 tons per square foot on some parts of the wall. Should the wall be constructed of porous material, the shock will be transmitted by the interstitial water to the sheltered side and compress any air there may be in the pore spaces of the wall; when the wave retreats, it exerts a suction on the blocks which, with expansive force of the air within the wall, may result in some of the blocks being drawn out of the wall. Further, the downward rush of the descending wave may seriously scour the toe of the breakwater. Re-entrant angles in plumb-faced breakwaters will merely intensify all these effects. These dangers may be reduced by building the breakwater to take a glancing blow; but at the same time it is necessary to avoid diverting the waves across the passage through which vessels pass, because they may not be able to enter during a storm. An ordinary beach is the most effective protection against storm waves because the force of the sea is expended in driving the pebbles up the beach. For this reason, the ideal sea-wall would be one with a sloping seaward face composed of great, loose blocks so arranged that they would successively follow each other up or down the slope when driven by the incoming waves or dragged by the receding seas. The nearest approach to this is the low seaward slope of a wall which engineers term an "expending beach."

CHAPTER II

TUNNELS AND SHAFTS

THE location of a tunnel, like the site of a bridge, does not often allow of much freedom of choice. A tunnel either becomes necessary at a given place in order to maintain an alignment through a mountain range or the spur of a ridge, or it is an advantageous alternative, in avoiding hilly obstacles, to an otherwise long or difficult detour.

The most important considerations in a projected tunnel are that the rock will stand cutting and that the work will not be rendered unduly expensive owing to hidden sections of

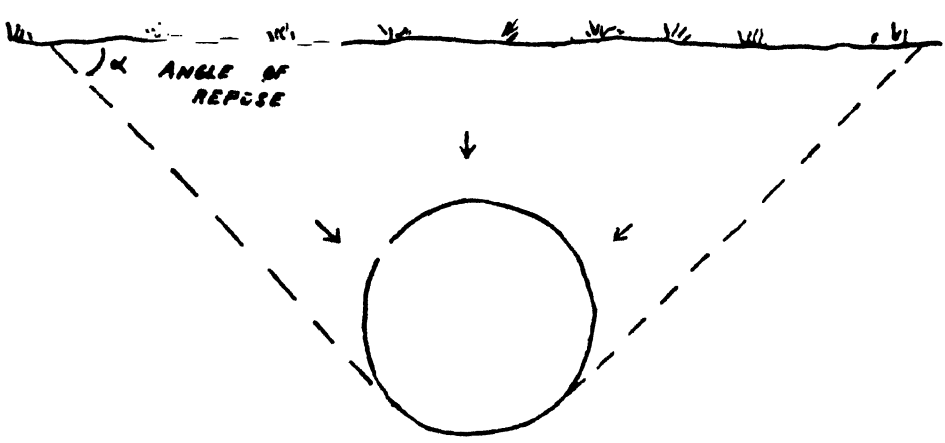


FIG. 21.

Tunnel driven at a shallow depth is subjected to the full weight and thrust of the overlying unconsolidated material.

"running ground," large volumes of water, excessive rock temperatures or the discharge of noxious gases.

If an exact idea of the structure and nature of the rocks of an area have been determined by a detailed geological examination, it is generally possible, unless the rocks have been subjected to exceedingly complex folding, to predict the conditions likely to be met with in driving a given tunnel.

Tunnels in Loose Ground.—Tunnels driven at shallow depths, 50 feet or so, in loose or unconsolidated rock require lining. They have the characteristics of retaining walls. Two

retaining walls facing each other and the space between arched over would give a tunnel. Shallow tunnels are consequently subject to the thrust of the unconsolidated material on each

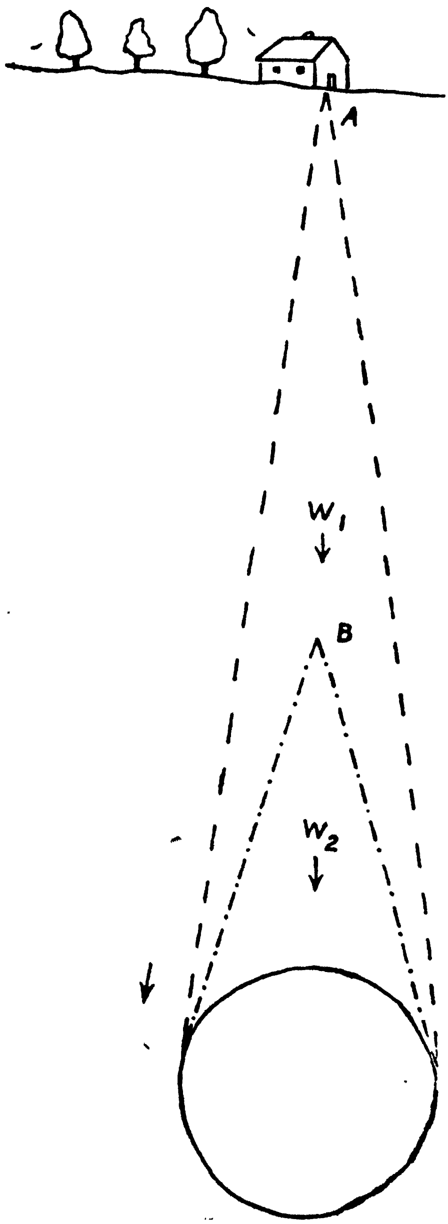


FIG. 22.

Tunnel at moderate depth in stiff clays will not be subjected to the full weight of the superincumbent strata.

side, and the arch of the tunnel has to bear the weight of the superincumbent material (see Figs. 21 and 22). Drivages of this description are subject to continual falls of roof and sides,

and necessitate elaborate precautions during the operations of tunnelling.

At somewhat greater depths, 100 to 150 feet or so, the unconsolidated material stands better if it is not heavily soaked with water. It often happens that, although falls of roof and sides take place frequently, the work of driving may not prove as difficult as in making shallow tunnels. If the ground is firm, there may even be less weight on the arch of the tunnel lining and less thrust on the sides. In stiff, moist clay these pressures may be very much less, because the cohesion of the material is fairly strong and the angle of repose may be steep. Wet, incoherent ground, such as gravel or sand or clay, is always troublesome and constitutes "running ground."

Tunnels in Consolidated Rock.—Tunnels driven through

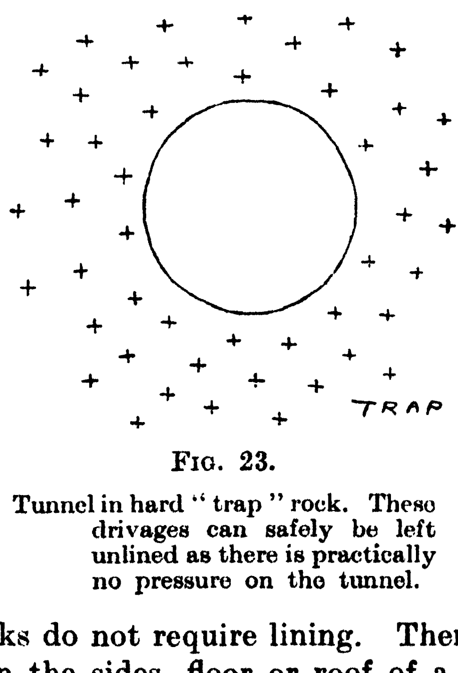


FIG. 23.

Tunnel in hard "trap" rock. These drivages can safely be left unlined as there is practically no pressure on the tunnel.

hard, massive rocks do not require lining. There is generally no pressure acting on the sides, floor or roof of a tunnel driven in granite and other large masses of igneous rock. Occasionally tunnels, for part of their length, may traverse massive beds of sandstone or limestone with the same advantages. In these cases, the presence of joints in the rock, particularly if it is hard, make the work of tunnelling much easier and cheaper.

Long tunnels usually traverse various kinds of rock—these may consist of a complicated series of gneisses and schists, or beds of folded or tilted sedimentary strata. The alignment of the tunnel may be oblique to, or parallel with, the banding of the strata. A tunnel may cross the line of a fault, or pass through beds in the arch of a fractured anticlinal fold, or it

may be cut through the strata in the trough of a synclinal fold. The beds themselves may vary from strong, porous sandstones to soft impervious shales, and be gently or *steeply inclined.*

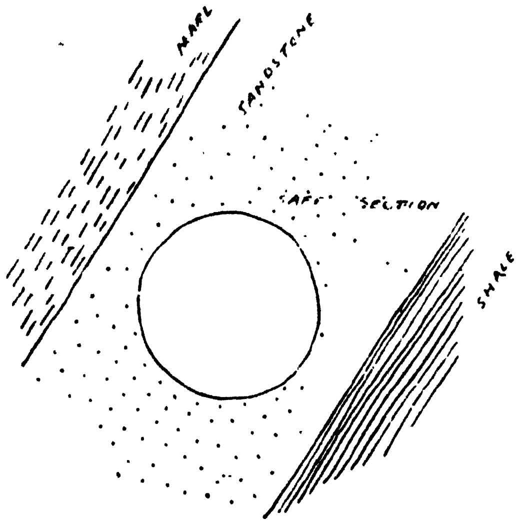


FIG. 24.

A tunnel driven along a massive bed of sandstone. The strata, although steeply inclined, do not affect the tunnel if the sandstone is very thick.

Tunnels Driven along the Strike.—Various examples of tunnels driven along the strike of bedded rocks are shown in the accompanying cross-sections (Fig. 23, 24 and 25). In Fig. 23

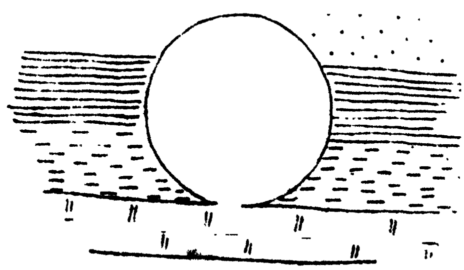


FIG. 25.

Tunnel driven in thin, bedded, horizontal strata. A bed of hard sandstone has been utilised to form the roof of the drainage.

the tunnel is shown in a great mass of trap (dolerite). These rocks are fairly hard and tough, and usually well jointed. The work of driving should not be very expensive unless large

volumes of water are suddenly discharged from the larger joint fissures. Such a tunnel will not require lining. Fig. 24 represents a tunnel driven along the strike of a massive bed of sandstone. If the rock is open-textured, the tunnelling operations will be easy though a steady inflow of water may have to be dealt with. The tunnel will not have to be lined. In Fig. 25 the tunnel is driven in horizontal strata. Most of the tunnelling has been done in soft rock, shales and marls, and a strong sandstone is left to form the roof of the tunnel while a hard limestone is exposed in the floor. This tunnel should not require lining if the sandstone is not heavily jointed. A certain amount of water will probably percolate into the tunnel, but this should not prove expensive to drain.

Fig. 26 shows a tunnel driven along the strike of tilted strata;

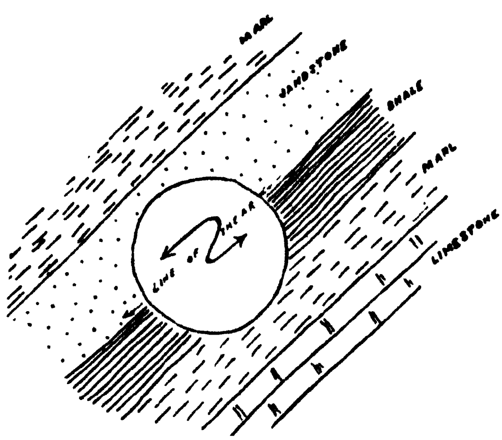
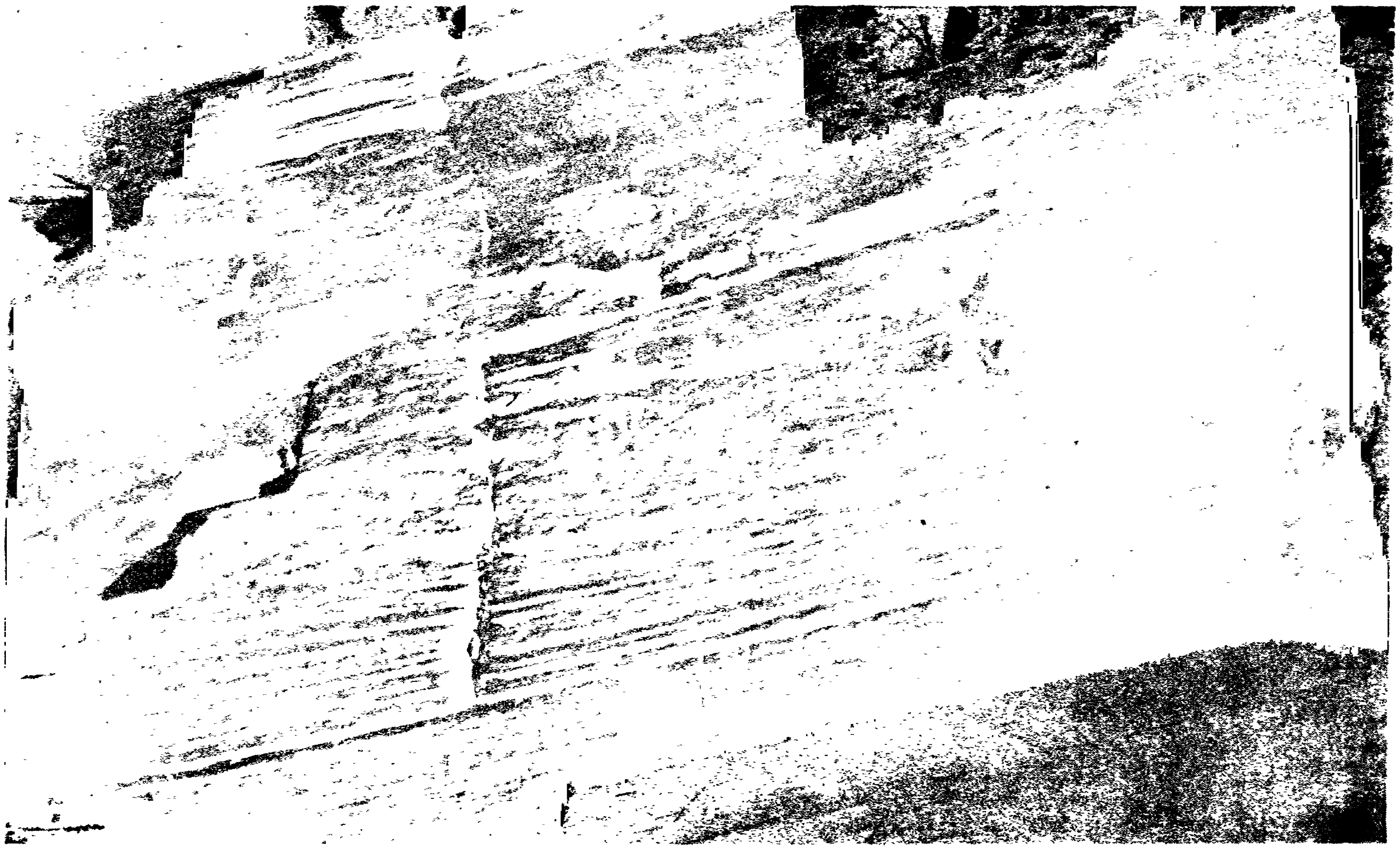


FIG. 26.

A tunnel driven in inclined strata may be subjected to shear stresses owing to the beds tending to slide over each other.

part of the section is in soft shales and part is in strong sandstone. If the rocks are dry there may be little or no trouble, but if there is an inflow of water along the junction of shales and sandstones in the roof of the tunnel, it may be better to avoid the sandstone by cutting the tunnel so as to touch the underlying limestone. In doing this the water troubles may be avoided, though in any case the tunnel will probably require lining to prevent falls of roof. There is, however, another danger. This is due to the possibility of relative movement between the hard and soft beds. In consolidated strata, consisting of hard and soft beds, there is, if the strata are tilted, a tendency for the hard beds to slide over the softer, lower beds on their plane of contact. This would

PHOTOGRAPH II.



With the permission of D. G. S. I.] [*Photo by Dr. A. M. Heron.*

SHOWS THE BUCKLED CONDITION OF A SOFT LAMINATED BED DUE TO THE RELATIVE MOVEMENT OF THE UPPER AND LOWER BEDS. ARAVALLI LIMESTONE, BANSWARA STATE, RAJPUTANA.

be likely to take place between the sandstone and the shale —particularly if the rocks were wet—consequently this danger would also be avoided by locating the tunnel to the right of the position shown in Fig. 26. In Fig. 27 the tunnel is driven along the strike of vertical strata. The same general remarks made with regard to Fig. 26 apply to this case. If the tunnel were cut entirely across the hard sandstone, an enormous weight might be suddenly brought to bear on the tunnel, owing to the sandstone being only supported by the friction of the beds on each side. If the tunnel were entirely in the shale and marl, this danger would not be so great owing to the greater cohesion of these beds. A lining would probably be more necessary in this position as there are likely to be frequent falls of roof.

In the tunnel sections just described, there are not likely

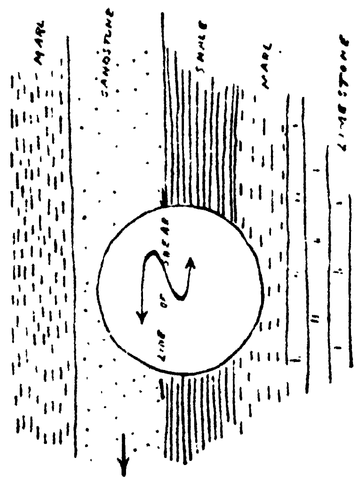


FIG. 27.
A strike tunnel driven in vertically inclined strata. The danger from shear forces will be greater than in Fig. 26.

to be sudden, enormous inrushes of water. Hot springs and noxious gases, if present, would betray their presence long before they were actually met with. The strata throughout the length of the tunnel would have the same general characteristics.

Tunnels Driven across the Bedding.—When a tunnel has to traverse successive beds of different rocks, the work of tunnelling will not be uniform. Water troubles may be local and sudden, because water is nearly always encountered when a tunnel crosses tilted strata composed of alternate porous and impervious beds. The danger from relative movement of the beds will also be present if hard and soft beds alternate. If the rocks are not folded and the succession of the beds and their inclination have been correctly ascertained, most of these troubles can be anticipated and efficiently dealt with. In folded strata, the problem is far

more complicated. The inclination of the beds must be carefully watched. There is usually cause for vigilance when the strata show a gentle inclination or dip, because this is an indication that an arch or trough fold is being approached. The greatest watchfulness is necessary when the alternate beds are different in character—e.g. sandstones with shales—and the folds are sharp (see Fig. 28). There is usually less danger from falls of roof in tunnels driven across the bedding of steeply inclined strata than is the case if the beds are gently inclined. With unconsolidated rock, this danger is greater than with more compact rock. Earthy sandstones, stiff marls and shales sometimes stand very well at the time of cutting, but frequently crumble on exposure; consequently, if tunnels in such rocks are not lined in a reasonable time, bad sections may develop.

Hot Springs and High Temperature.—Hot springs can

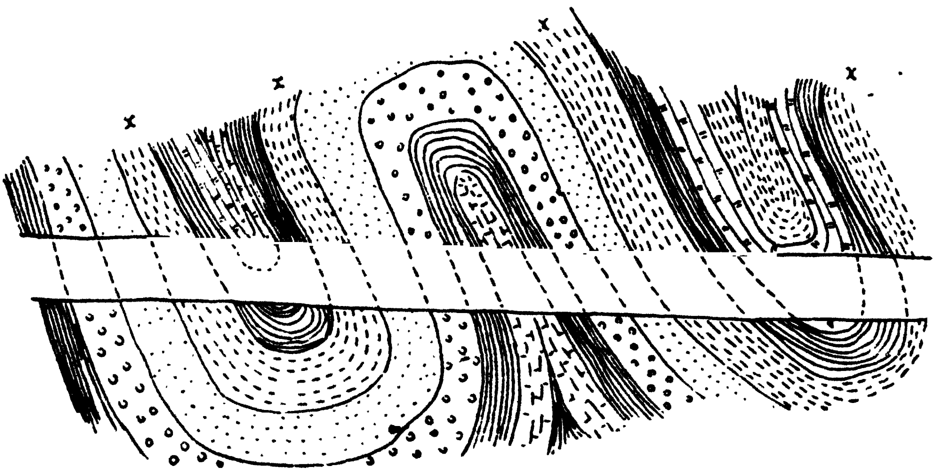


FIG. 28.

Tunnel driven across folded strata.

usually be detected in the neighbourhood of a tunnel. If none are on the surface, their occurrence in tunnels, except under high mountains, will be rare. If met with in the deeper drivages, it will usually be possible to dilute the hot water with the colder water of other springs in the same tunnel.

The rock temperatures encountered in various long tunnels driven deep under mountains have so far not been found to seriously affect the working operations, when compressed air drills and heading machines have been used. Coarse-textured, igneous rocks seldom influence the air temperatures to an uncomfortable degree. The most troublesome types are usually carbonaceous and argillaceous beds in which the mineral iron pyrite is present in appreciable quantities. This substance is

liable to oxidation when exposed to moisture-laden air; and, if the beds containing it are not sealed from the air, the beds may become hot, and carbonaceous matter, if present, may become ignited by spontaneous combustion.

Noxious Gases.—Certain limestones, carbonaceous beds and pyritiferous, argillaceous rocks are the usual varieties of strata from which noxious gases are evolved. Accumulations of gas may be present, or the gases may be given off gradually when particular beds are exposed. However, these dangers can usually be suspected during the preliminary geological examination by the detection of iron pyrites, oil or alkaline substances in the associated rocks. The harmful effects of such gases can generally be greatly minimised by establishing an efficient system of ventilation and by carefully sealing these particular beds when they are encountered.

Tunnels in Trough Folds.—Tunnels which are driven across

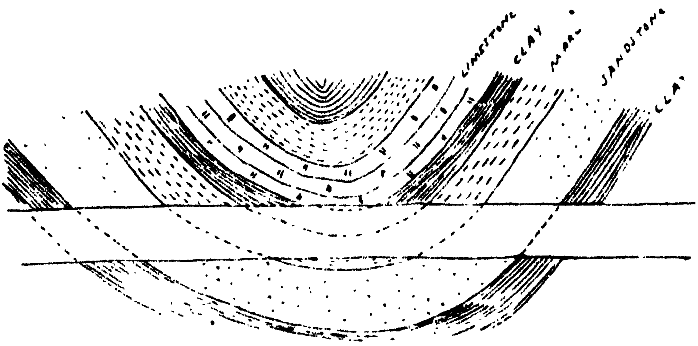


FIG. 29.
A tunnel driven through a synclinal fold of the beds.

the axis of a trough fold of the strata may encounter serious water difficulties and be subject to falls of roof (see Fig. 29). Splendid artesian conditions may exist, so that when the tunnel taps a porous bed enormous volumes of water under great pressure may be discharged into the tunnel. If hard rocks occur, it is probable that water will occur in the numerous joint-planes. Also, owing to the jointing being radial to the curve of the folds, the resulting blocks will have the shape of inverted keystones. These may suddenly fall into the tunnel with fatal consequences.

A tunnel driven in and parallel to the axis of a syncline will naturally be subject to these rock-falls to a greater degree, because such dangers are present throughout the length of the section in the syncline.

Tunnels in Arched Folds.—There is, as a rule, less likelihood of serious water trouble in sections where a tunnel cuts across the axis of an anticline in bedded rocks than in inclined strata.

There is also less danger from sudden rock falls, because the blocks will be in the shape of keystones and consequently are unlikely to fall into the tunnel. If, however, the rocks are severely crushed, as they sometimes are on the lower side of the arched fold, the shattered material may cause small falls of roof. Similar remarks apply to that length of a tunnel which is driven parallel to the axis of an anticline (see Fig. 30).

Tunnels Driven Across Faults.—A tunnel should never be driven along a fault which has not been mineralised. The plane of a fault is usually a zone for the release of earth strain. Displacements of the rock on each side of the fault frequently take place, and this movement may lead to the destruction of the tunnel.

Enormous volumes of water are frequently present at points where a tunnel crosses the plane of a fault—particularly if porous

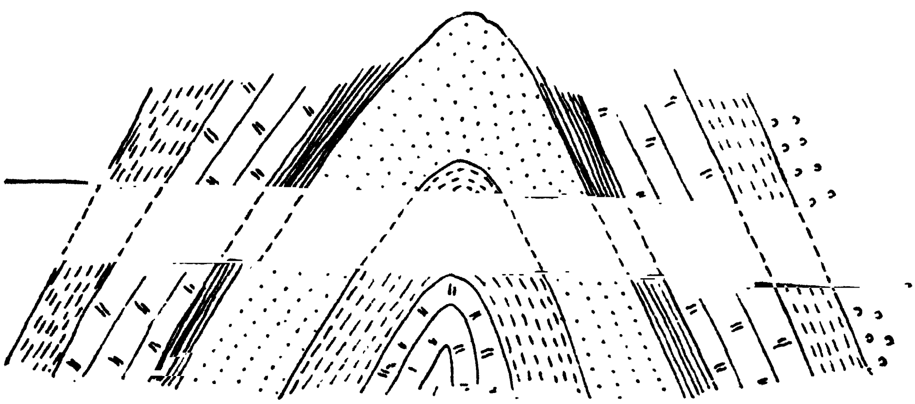


FIG. 30.

Shows tunnel through an anticlinal fold of the strata.

beds on one side dip towards impervious beds on the other side of the fault plane. Relative displacement of the strata on opposite sides of the fault-plane are an obvious source of danger, more especially if the rocks on both sides of the fault are well consolidated beds of hard material. In less-consolidated strata, this danger may often be more imaginary than real. Cases are known, e.g. the mile-long Barog tunnel on the Kalka-Simla railway, where a tunnel, which traverses beds of hard rock, crosses a fault and enters softer rocks, has not been damaged by a severe local earthquake. The shock of the earthquake appears to have been absorbed by the compressibility of the softer rocks of the tunnel under consideration. If thrust faulting is present and the beds involved are soft or soluble, e.g. limestones or salt marls, dangerous falls of roof are almost certain to follow excavation in these places, and serious water troubles are seldom

absent from such conditions. In any case, an exceedingly strong lining will be required in these sections. If the plane of the thrust fault is inclined at a low angle, the tunnelling through the section of dangerous ground may prove too costly to be carried out.

Water in Tunnels.—The amount of water and the rate of its discharge into the tunnel depends on numerous factors. Among the more important of these are : the contour of the hill through which a tunnel is to be driven, the extent of the out-crop of a porous bed and the slope of the ground on which this bed outcrops, the jointed nature of the rocks and the presence of faults. Less water may be encountered in open-textured rocks which out-crop on precipitous hill-sides than may be expected ; whereas fissured rocks which are exposed on level ground may contain large volumes of water.

Pressure Tunnels.—In many cases, tunnels are lined in order that the tunnel may be kept free from falls of loose rock or from an influx of large volumes of water. The lining of the tunnel is, therefore, subject either to the weight of the loose earth, or to the pressure of the surrounding water, or both. Occasionally, a tunnel acts as a duct for a canal ; and, more rarely, a tunnel may function as part of a pipe-line for water under considerable pressure. In such circumstances, it is obvious that there will be an outward pressure on the lining of the tunnel.

The Sutlej River Hydro-electric Scheme includes a projected tunnel, a mile long, which is designed to conduct water under a 160-foot head, when the great 395-foot high Bhakhra dam is built. This pressure of water, which is approximately 70 lbs. per square inch, is as great as the pressure in many boilers. Water, under this pressure, would burst most masonry linings if the strata behind the lining were not incompressible. In hard rocks, if the joints are carefully grouted up, there would probably be no necessity to line the tunnel. Limestones, however hard, are always soluble, and it would be unwise to leave those sections of a tunnel unlined in which soluble rocks were exposed. There would not only be leakage of water from the tunnel, but, in time, this escape and its solvent action might result in a collapse of a portion of the tunnel.

Most rocks, including soft sandstones, can be treated as incompressible if exposed to pressures not exceeding 400 lb. per square inch. Sand and gravel, if unable to escape laterally, will also, for practical purposes, be incompressible under these pressures. Tunnels through these rocks would in any case be lined ; so that, if a little care were exercised to ensure the loose material behind the lining being rammed into place, there need

be no fear of the tunnel being burst by the "give" of the lining. Clays, on the other hand, are compressible even when subject to moderate pressures; consequently, tunnel sections in clayey strata require special treatment, e.g. by putting in steel tubbing or casing, etc.

Shafts.—The location of a shaft for mining or engineering purposes is usually fixed after making a geological examination of the area of the proposed site. Frequently the actual spot is chosen after boring. The cores of the boring provide information of the kind of rocks which will be encountered.

In the case of long tunnels these shafts serve a treble purpose. They supply data for each section of the tunnel, allow of greater speed in tunnelling and do away with elaborate ventilation. For example, in the projected Lochaber water-power scheme in Scotland the longest tunnel will be 16 miles long. At least 14 shafts are to be sunk from the surface to the line of the tunnel to give twice that number of points from which to work in addition to the two ends. This procedure is sometimes modified in driving tunnels under rivers. In making the tunnel under the Thames, between Stepney and Rotherhithe, an entry was effected to the line of the tunnel by means of caissons fixed in the river itself. The cross-channel tunnel will, however, necessitate special operations as both shafts and caissons are impracticable. In this case it is known that some of the strata are continuous, although not in an absolute straight line, from shore to shore. The proposed scheme, therefore, aims at working from either end in a particular bed. If an impervious stratum is chosen and the bed is sufficiently thick, the only drawback to the scheme is the time which will be taken in tunnelling from two working points and the arrangement of efficient ventilation.

CHAPTER III

STABILITY OF HILL-SIDES

LANDSLIDES are familiar troubles in most countries where roads, railways and canals have been made through hilly country. The difficulty of keeping the Panama Canal open is largely due to the unstable condition of the sides in certain sections of the country. The expense involved in holding up these unstable sections of a road or canal is always considerable if the material cannot be permanently held.

Landslips occur when by natural processes the unconsolidated,

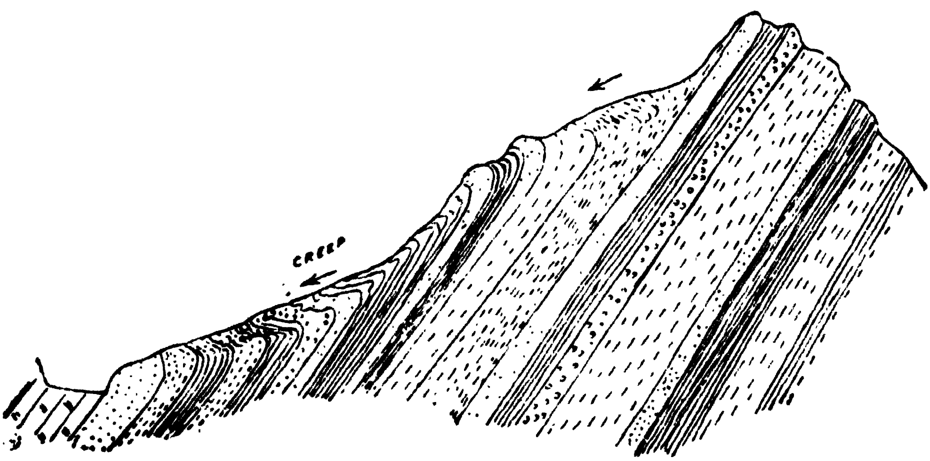


FIG. 31.
"Terminal creep" in the out-crop of soft bedded rocks.

loose materials or the jointed masses of rock of a hill-side detach themselves and slide down. The loose material, soil, gravel, etc., on most hill-slopes, tends to creep or slide down to a lower level. If the hill-slope exceeds the angle of repose of this material a sudden slip or a gradual creep will take place, unless the loose material is held up by vegetation or by artificial means. The slope, however, will be unstable.

Creep.—The tendency to slide is so strong that on bare, fairly steep slopes in which bedded rocks are hidden by a few feet of soil, a drag is exerted on the underlying rocks. If the rocks are steeply inclined (see Fig. 31), the upper part of the beds may

be bent over and give quite an erroneous idea of the true dip of the strata. This structure is known as "terminal creep," and is sometimes of considerable importance to the engineer. For example, in Fig. 31, supposing a dam had been built across the valley, the impounded water would wet the incoherent material, thereby reducing its angle of repose and cause it to slide into the reservoir. The movement of this material on the lower slopes would disturb the angle of repose of the material higher up and possibly result in other landslips, which might seriously reduce the volume of water stored in the reservoir. If a pressure tunnel had been put through the hill in the section shown in Fig. 31, the tunnel would certainly be choked and the supply of water cut off (see also Fig. 32).

Angle of Repose.—The angles of repose, ϕ, of various materials.

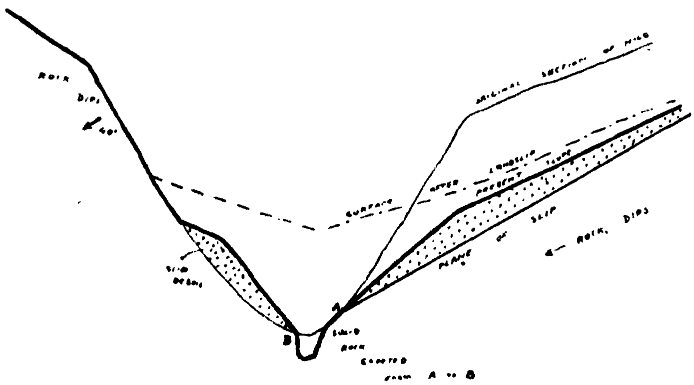


FIG. 32.

The section shows a river bed which was filled by a landslip. The river-lake which resulted finally overflowed and re-excavated its valley. The debris of the landslip is shown on each bank. This material is continually subject to slide owing to the angle of repose of the material being variable in dry and wet weather.

sand, clay, etc., are fairly well known within certain limits; i.e. for earth and loam it varies from 30° to 45°, for moist sand it is about the same—30° to 45°; in clay it varies from 25° to 45°, gravel 30° to 40°, dry sand 25° to 35°, wet sand 15° to 30°, etc. Consequently these materials will not remain on hill-slopes of the same inclination as their angle of repose. The "creep" is greatest in very wet weather, particularly after long, dry spells. The expedients of planting shrubs, cutting vertical drains, etc., to hold the incoherent material, are well known to all engineers. The cutting of a herring-bone system of channels down the slope, or special drainage tunnels to take off the water, are other methods of protecting hill-sides. However, this opens up an aspect of the subject in which the remedy sometimes

proves worse than the " sickness "—for, in some cases, by draining away the water from moist material, the angle of repose may be decreased and larger slips may be caused. This is said to have occurred in the Panama Canal. When hard, massive rocks, granites, dolerite or thick beds of sandstone, quartzite or limestone, are exposed on hill-slopes, the hill-side may be perfectly safe at all angles up to vertical precipices. A hill-side with thick, bedded rocks may, however, be liable to enormous landslips. The conditions for these depend on the direction in which the strata is tilted, their degree of inclination and the nature of the beds involved. There is always a tendency for an upper bed to slide upon the stratum below—particularly if the strata consist of alternating hard and soft beds. The principles are the same as with loose materials although the constants naturally differ.

Co-efficient of Friction—The co-efficient of friction of repose (i.e. tan ϕ (angle of repose) = co-eff. of friction) gives the angle at which a plane surface can be tilted before movement takes place. These co-efficients have not been accurately obtained for the various kinds of rock, but sufficient is known to enable the engineer to know the danger angle of such strata. In this connection the following co-efficients of friction are of value :—

	$\tan\phi =$
Masonry on wet mortar..	0·75
Hard brick on hard brick	0·70
Concrete blocks on concrete blocks	0·65
Dry masonry on dry masonry	0·60 to 0·70
Masonry on dry clay	0·50 to 0·60
Masonry on wet clay	0·33
Earth on earth	0·25 to 1·0

Coarse-textured rocks, conglomerates, grits, sandstones, quartzites, when not badly fissured and not interbanded with soft rocks, appear to have an angle of repose as high as 35° or more. Soft rocks, fine clay-slates, slates, shales, etc., have a limiting angle at about 28° when dry, and less when wet. The worst condition occurs when interbanded, hard and soft rocks are found tilted at about the angles given above.

Inclined Bedded Rocks.—Figs. 33, 34, and 35, show sections of a hill-side with inclined strata. It is clear that the dips must be in the same direction as the slope of the hill in order that the overlying rock masses can slide clear and form a landslip. The danger is naturally greater in thin beds, because there are so many more inclined planes on which the slips can take place. In Fig. 33 the beds are shown dipping at an angle greater than 30°, with a free out-fall towards the river; consequently the conditions are present for a great landslip. Fig. 34 shows a hill-

slope with an inclination of 40°, with beds dipping at about 32°. The beds consist of hard, schistose quartzites with intercalated

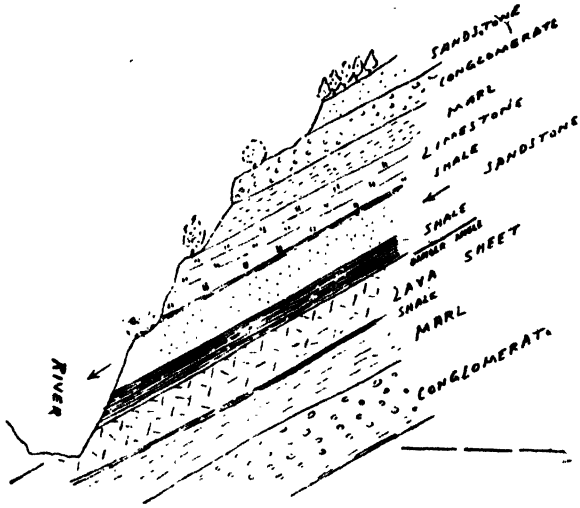


FIG. 33.

Shows an unstable hill-side owing to the strata dipping towards the river and thereby having a free out-fall.

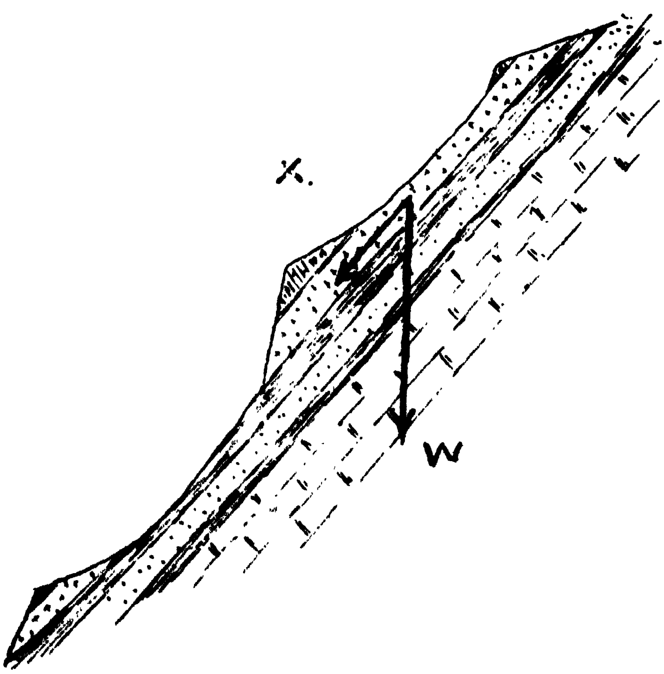


FIG. 34.

An unstable hill side which is liable to local slips.

layers of clay-slate. In this case a portion of the hill-side is dangerous and may be loosened by cutting a road in the

concave part of the slope. Fig. 35 represents a section where the dip of the strata is greater than the slope of the hill. The hill-side,

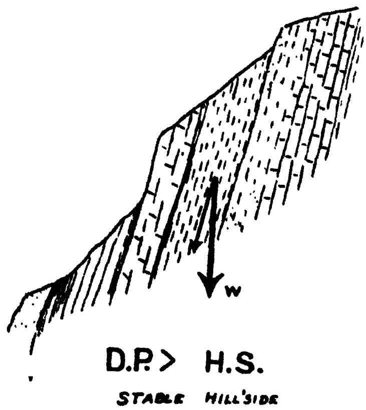


FIG. 35.

A safe hill-side. The strata dip (D.P.) more steeply than the hill-side (H.S.) so that each outer bed holds up the next within.

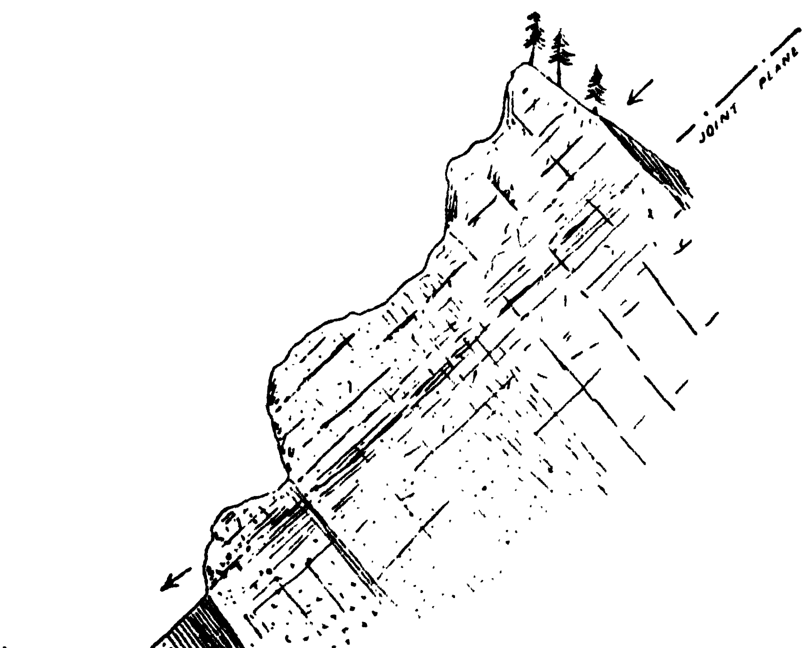


FIG. 36.

Shows an otherwise safe hill-side which became unstable owing to the development of a weak plane of slide.

although steep, is probably quite safe, because each successive bed is held up by the one below it. There is no free out-fall.

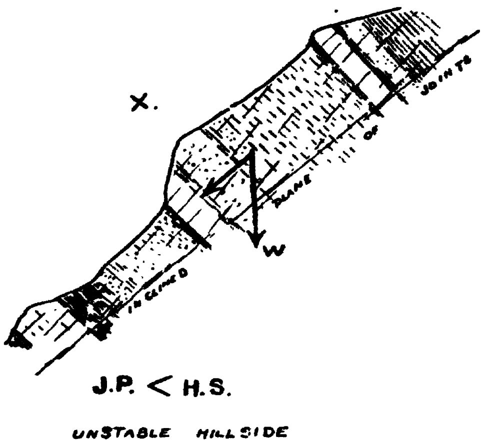


FIG. 37.
Shows how joint planes (J.P.) may function as planes for landslips and produce dangerous hill-slopes (H.S.).

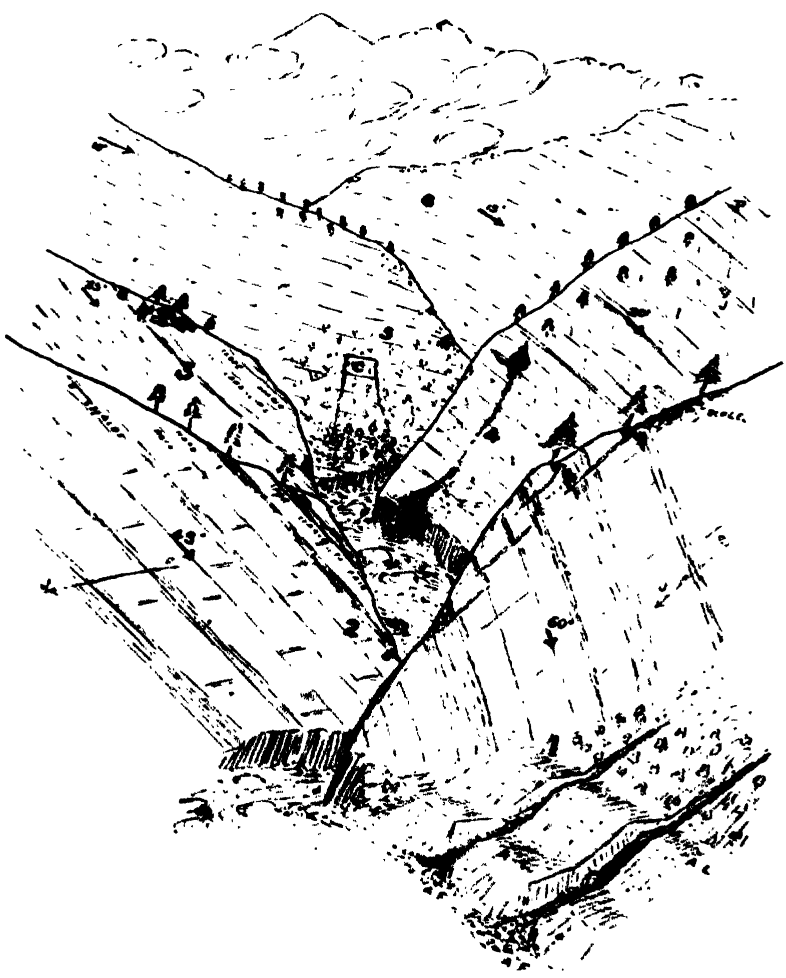


FIG. 38.
A view up a mountain valley showing defects in the stability of various hill-sides.

Joint Planes.—If the rocks dip into the hill, the conditions are better for safe hill-sides, unless a system of joint planes are present (see Fig. 36). Joint planes may often function as inclined planes if they are tilted towards the valley at suitable angles. Occasionally, irregular joint planes develop a perfect plane owing to the free out-falls and the tendency of the overlying material to slide clear (see Fig. 37). Thus it is seen how important well-developed jointing may prove in questions of this kind. In Fig. 38 a number of unstable hill-sides are depicted. This sketch represents various examples of unstable hill-slopes, which were actually found in a reconnaissance survey of a projected railway alignment in the Ganges valley of Garhwal in the Himalayas. In the foreground, on the right, two terraces are seen cut by ravines. These flats although composed of debris are well drained and quite firm. Spur 1 shows steep in-dipping strata on what would have been a safe slope, but, owing to the system of joints, this hill-side is liable to landslips. Spur 2 is clearly unsafe. The rocks dip steeply towards the river at a lesser angle than the lower slope of the convex spur and are consequently in an unstable condition. Spur 3 is similar to Spur 2 in structure, and although the dips are a little less, the beds consist of hard, doleritic gneiss with interbedded, greasy, talc schists. The hill-side is perhaps more dangerous than that of Spur 2. Spur 4 is perfectly safe from a structural point of view, but a bad face of fissured rock is exposed from which, in times of frost, pieces split off and form scree. This face of rock could, perhaps, be easily sealed up by a small masonry wall. Spur 5 is of interest in that the soil and subsoil has moved under the influence of its weight on the steep slope, carrying with it a forest-covered hill-side in a typical example of creep. The ominous bulge at the base first drew attention to the scar C above.

River Bends.—When considering hill-sides, it is necessary to examine the whole slope from the bed of the valley to the crest of the ridge and to take into account the curves of the stream. A landslip is generally more quickly precipitated, when unstable conditions prevail, at those places where the river makes a concave bend to a projecting spur. In such cases, not only is there a free out-fall, but the rocks are also free on either side. In a lateral valley the rocks are held in both directions along their line of strike.

As a general rule, therefore, it is best to *avoid, as far as possible, the side of a valley in which the rocks dip towards the stream at the danger angle but less steeply than the hill-slope—particularly when the beds consist of interbedded layers of hard and soft rock.*

CHAPTER IV

QUARRYING AND MINING

QUARRYING and mining are intimately connected with each other. In the former, the workings are open to the sky ; in the latter, the operations require overhead protection.

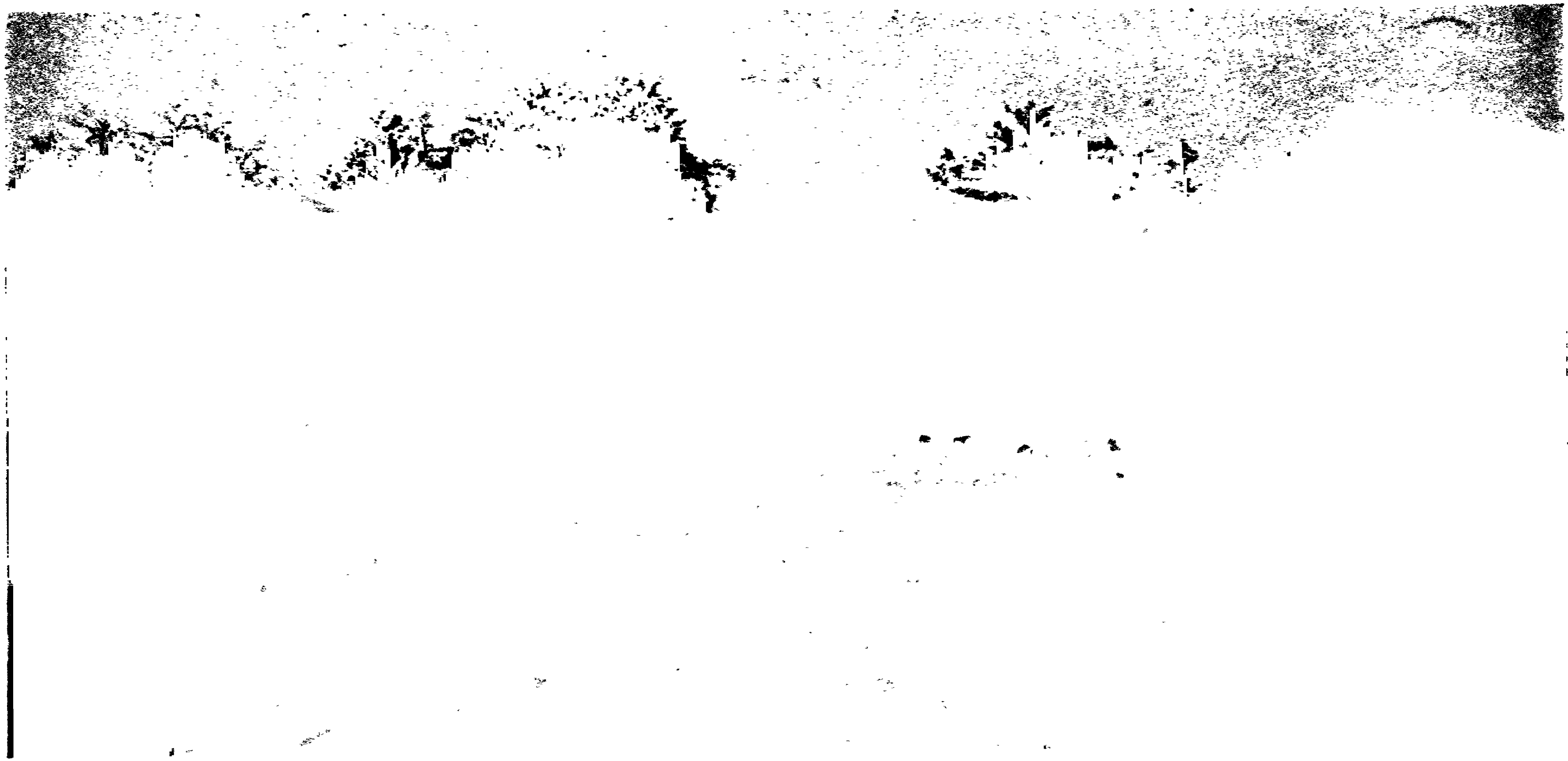
Quarrying in Loose Ground.—The location and opening up of a quarry often necessitates some exploratory work, as it is not always possible to see the unweathered or jointed nature of the rock.

The fundamental principle of quarrying is to arrange the working face in such a way that the rock can be easily freed with the least expenditure of energy and when free will slide forward under its own weight. In other words, quarrying aims at producing landslips for a useful purpose. If the material required is loose, incoherent gravel, it is usually necessary to keep the face of the quarry steeper than the angle of repose of the material. If the material consists of shattered rock which occasionally stands vertical, it may be necessary to undercut or blast it to enable the material to collapse into the quarry.

Quarrying Stratified Rock.—The same strategy is used in extracting blocks from bedded rocks. It is known that most hard rocks have three divisional planes, which are usually at right angles to each other. In Photograph III the beds of sandstone are seen to be nearly horizontal ; the bedding plane functions as one divisional plane, while the two sets of joints A and B function as the other divisional planes. With a little skill, it is possible to detach blocks of various sizes. Much, however, depends on the spacing of these joint planes. In slates the spacing of one set of divisional planes may be so close as to warrant the use of the name cleavage in designating them. Photograph IV shows a slate quarry. In this case the bedding plane (b.p.) although inclined is indistinct, while three distinct joint planes A, B and C—one nearly horizontal—are present. In neither of these cases is there a tendency for the liberated material to slide clear.

It is, however, common experience to find one of the divisional planes, either the bedding plane or a joint plane, in an inclined

PHOTOGRAPH III.



With the permission of D. G. S. I.] [*Photo by Mr. H. C. Jones.*

SANDSTONE QUARRY, BARO, BHILSA DISTRICT, GWALIOR STATE.

The bedding and two cleavage directions are well seen on the left of the photograph.

PHOTOGRAPH IV.

With the permission of D. G. S. I.] [*Photo by Sir T. H. Holland*

SLATE QUARRIES NEAR MONGHYR, BENGAL.

A = cleavage face, B = joint plane, C = horizontal joint plane, b.p. = original bedding.

position. When this occurs, the blocks or slabs slide forward when they are freed from the main mass of rock. Fig. 39 shows a sandstone quarry in which the beds are tilted. The bedding planes are well separated, the strike joints are distinct and the dip joints are less well developed. In this case, the rock is first freed by a deep cutting parallel to the dip joints, while the working face has been cleared on the dip side parallel to the strike joint planes. By careful wedging, with perhaps a little blasting and

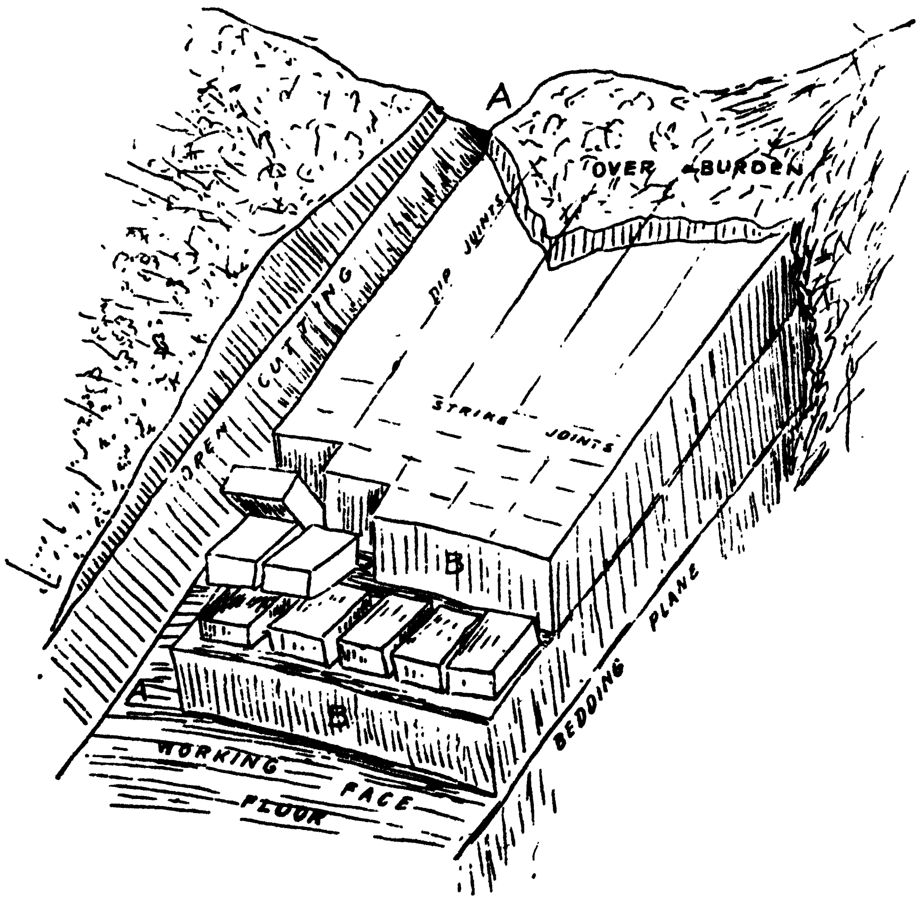


FIG. 39.

Sandstone quarry in inclined beds.
Shows side cut A-A parallel to dip. B, B, etc., are the working faces in the plane of the "strike joints."

undercutting, the separate blocks can be easily prized off the working face.

Occasionally, the joint planes intersect each other at angles other than right angles. An example of this kind is shown in Fig. 40. Here a slate quarry is depicted with diagonal jointing and an inclined bedding plane. One of the two divisional planes—the cleavage—is perfect, while the other is less distinct. To work this rock, the working side is made on the dip side.

Narrow, side cuts, A—A, are made into the rock along the indistinct joint planes and the slate is prized off along the cleavage planes.

In Fig. 41 steeply dipping beds of marble are shown. They are depicted with irregular, but distinct, joints. The workman takes advantage of these natural features to wedge and prize up the blocks and assist them to slide forward on the joint planes.

In more massive rocks, such as granites, etc., the joints may be far apart; consequently it may be possible to quarry blocks of great size. Blasting is generally necessary in these cases,

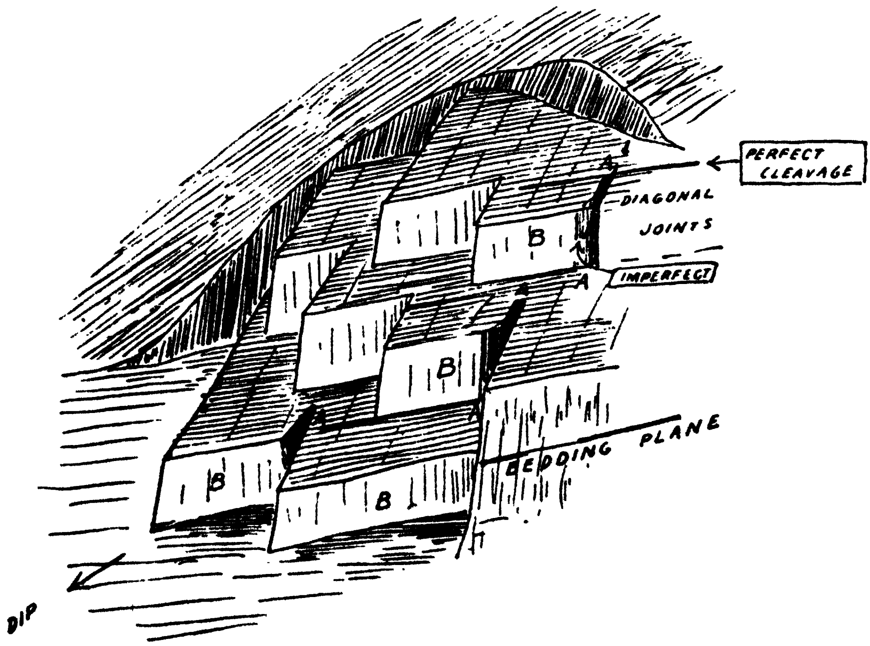


FIG. 40.

Slate quarry in tilted strata.

A–A are the cuts made into the slate in the plane of the poorest joints. B, B, etc., are the working faces in the plane of the perfect cleavage.

and the handling of the blocks may involve the use of elaborate appliances. The underlying principles, however, remain the same; i.e. to free the blocks along easily separable planes and to simulate the condition of weights on an inclined plane. If this is done, the cost of the work is very considerably reduced.

Mining Gently Inclined Beds.—In mining gently inclined seams of coal, it is usual to find the bedding planes of the floor and roof parallel and sufficiently distinct to allow of easy separation, both above and below. The "roads" or drivages are usually made down the dip and connected by cross-drivages on the level (i.e. parallel to the strike), because in most cases there is a well-

developed system of strike joints which are technically called the "cleat" of the coal. Then, starting at one or both ends of the level drivage, the coal is prized off the seam on the upper side; it falls forward into the level and is loaded and hauled away. In many cases, the coal has to be "holed" below or undercut. In some cases, the cutting has to be made above to free it from the roof. Blasting facilitates the work of prizing off the face.

If a seam of fire-clay is being worked, joints may not be sufficiently well developed and the material will have to be undercut and then blasted.

Conditions often arise when this ideal method cannot be

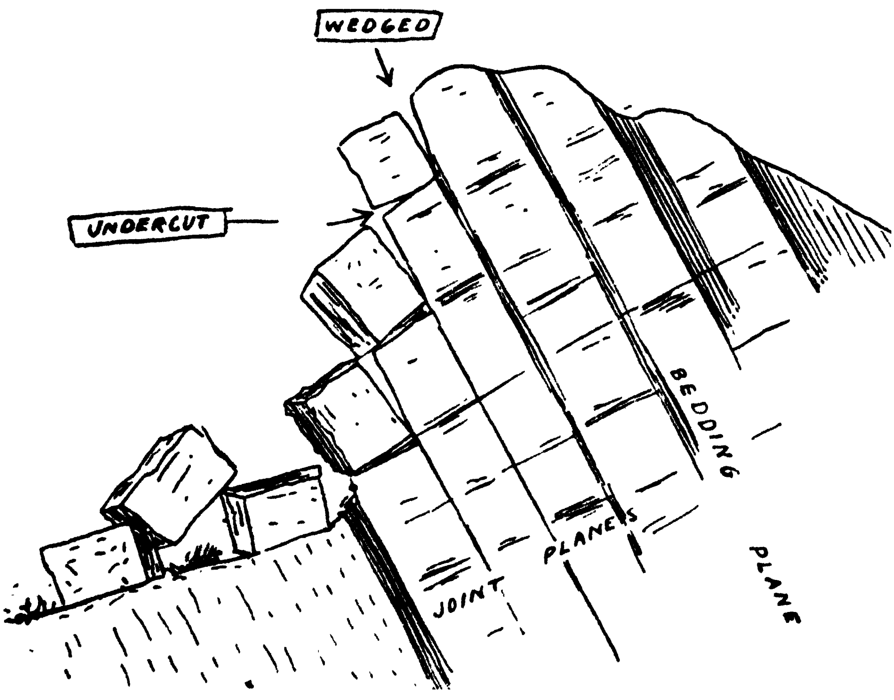


FIG. 41.

Out-crop of massive band of pointed marble. Shows method of quarrying.

followed. In these cases, the miner must use his common sense and take advantage of existing natural features.

Mining Steeply Inclined Beds.—Where a bed, or mineral vein, is nearly vertical, the best plan is to make drivages (levels), one below the other, at vertical intervals. These are then connected with each other by shafts or winzes. The rock may then be attacked in three ways: (1) the roof of each level may be directly attacked and the material allowed to fall in—this is known as under-hand stoping; (2) the floor of the level may be attacked and the material dropped down the winze into the level

below—this is over-hand stoping; (3) an intermediate level may be driven and the material attacked either by over-hand or under-hand stoping and the debris allowed to fall through subsidiary winzes, or hoppers, into the level below. Local conditions may, however, necessitate modifications, and the miner must then do the best he can under the circumstances.

Mining Loose Material.—Work of this kind invariably requires elaborâte protection for the workman. In these cases, the training of the mining engineer should help him to meet the conditions of the particular difficulties which present themselves.

CHAPTER V

BUILDING SITES

In the construction of valuable structures, such as bridge piers, etc., which involve the public safety, every conceivable engineering aspect of the design is most carefully investigated—with the result that the finished work is often deserving of public gratitude. The architectural design, however, frequently receives more attention than the suitability of the site to accommodate those structures. There is generally some latitude with regard to the final selection of the site for an important building, whether it is within the prescribed limits of a town or in connection with a project for building a new city. In other cases, there is usually still greater freedom of choice.

Each site requires a thorough investigation of the nature and structural features of the underlying strata. In all cases, the rock must be capable of supporting the weight of the building which is to be built upon it. On sloping ground it is essential to ascertain the stability of the slope. The presence or absence of faults should be established—particularly in areas subject to earthquakes.

Alluvial Ground.—The loads which can be safely borne by different kinds of material have been briefly stated in the chapter on Retaining Walls. The importance of suitably distributing the pressure, due to the weight of great buildings, is well known. In the case of the Victoria Memorial in Calcutta, a large expenditure was incurred in constructing an elaborate concrete "raft" on which this magnificent building was finally built. Some of the piers of the Hardinge (Ganges) bridge over the river, near Sara, are founded on wells which were carried down to depths exceeding 150 feet below low-water level. In this case, the only serious criticism of the work has been that the wells were sunk unnecessarily deep. The value of good foundations is, however, well illustrated in the leaning tower of Pisa. There, although the structure itself has obviously been strongly built and well bonded, the foundations were not sufficiently secured, with the result that the unequal settling became apparent.

Slopes.—Enough would have been said on this aspect of

the subject were it not for the fact that within the limits of the County of London there are examples of this kind. St. Paul's Cathedral is from time to time brought to public notice because of the weakness of its foundations. In other parts of the London district, particularly on the gravel slopes of the suburbs to the south of the Thames, there are buildings which have been involved in the subsoil creep and several houses have had to be "shored" up. Although sand and gravels are supposed to have definite angles of repose, these constants vary with the dry and wet condition of the material. However, the expansion and contraction of the particles, caused by the diurnal variation of the temperature, induces a tendency for the loosened material to gravitate *en masse* down the slope. If, in addition to these influences, the bed of gravelly material overlies a sloping rock surface, it is evident that creep must occur. It is, therefore, not surprising that the walls of several buildings in the area indicated are traversed by cracks. If the walls of houses built on gravel slopes show cracks, it requires little imagination to picture the effect on large water-mains which are laid horizontally across such slopes.

Continuing the argument to river banks with moderately steep slopes of similar material, it would seem that the same agencies must be at work. This gravitative movement would possibly be accentuated by the thrust component of the weight of heavy buildings which may be built on such river sides.

These considerations would probably not apply in the case of beds of stiff clay and may be absent when hard rock is exposed.

Earthquakes and Faults with regard to Buildings.—The prevailing opinion is that earthquakes are the result of the dislocation which follows the release of strain in the rocks of the earth's crust. Faults are the planes along which such dislocations take place. A fault once formed continues to be a plane of weakness along which further movement is likely to take place. Several faults are known on the opposite sides of which the strata have been displaced by upwards of 1,000 feet. This relative movement has seldom taken place at once; it usually represents the accumulated displacements of countless small movements, and thus a geologist speaks of the growth of faults. The line of a fault is consequently an unsafe place upon which to build an important stone structure. Some regions are particularly liable to earthquakes, and in these areas certain types of buildings are less suitable than others. Stone buildings built of large blocks of comparatively brittle rock are generally more liable to destruction than well-bonded brick buildings. There is more elasticity in the greater

bonding and less inertia in the individual bricks of the latter type of structures when they are subjected to the rapid oscillatory movements of an earth tremor. In the former class of buildings, the heavy individual blocks are liable to develop independent movements and may become separated and result in the collapse of the structure.

The Quality of Water used in Building Operations.—In the chapter on "Choice of Materials," particulars are given regarding the use of clay containing certain salts for the manufacture of bricks. It is there shown that such salts may cause a disfigurement of the appearance of the brickwork by the formation of an encrustation of salts on the exposed surface of the walls. This growth of an efflorescence may also occur on the face of walls which are built of other porous material, e.g. sandstone, if the water used in the building operations is heavily charged with similar salts. The saline water will be absorbed by the porous material and the salt will be deposited on the surface from which the contained moisture is slowly evaporated. It is thought that this case resembles that of a green log which being heated at one end exudes sap from the other. The explanation offered is that the expansion caused by the heat enlarges the size of the pore spaces on the sunny side of the wall and increases the capillary movement towards the cooler face, with the result that the saline water will concentrate on this side and by subsequent evaporation produce an efflorescence on the surface of the wall.

The waters most liable to cause this disfigurement are those which contain soluble carbonates, sulphates and chlorides of potassium, sodium, calcium, magnesium, etc.

The most efficient method of dealing with the saline waters which contain only sulphates and carbonates is to add a mixture of barium carbonate and barium oxide. By this means, both the temporary and permanent hardness is removed, insoluble sulphates are formed, free lime is liberated, and this helps to remove the temporary hardness due to the carbonates of calcium and magnesium. There is no simple, cheap method of removing the soluble chlorides, so that it is better to avoid using waters containing chloride salts.

Occasionally the lime of the mortar or cement contains magnesium sulphate or other soluble salt. These are dissolved in the process of building, with the result that the solution penetrates into the porous rock or brick and finally forms an efflorescence on the exposed surface of the wall. In such cases, the deposit may be removed by gently sponging the surface with very weak hydrochloric acid.

In some instances, where precautions have not been taken, the surface of good sandstone masonry becomes friable owing to the accumulation of saline matter in the interstices of the rock, with the result that ugly scaling takes place. No external application of preservative will save the facing, because the trouble is from within the masonry.

PART III

Building Materials

CHAPTER I

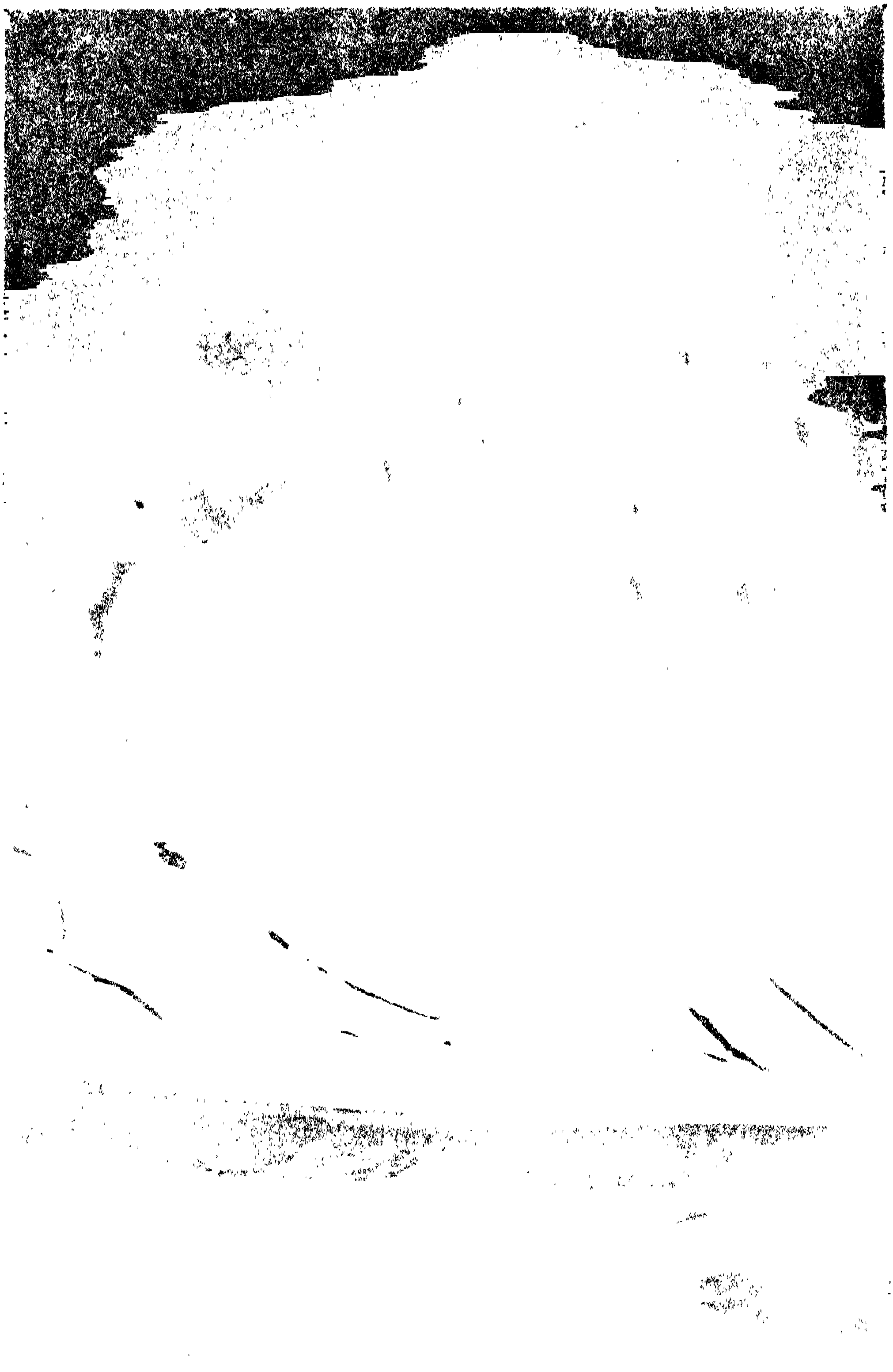
MODE OF OCCURRENCE OF ROCKS

In many parts of the world, particularly along the sea coast, there is evidence either of a subsistence of the land or a regression of the sea within the last hundred years. Closer investigation has shown that very marked changes have taken place in the geography of some countries during the historical period. Geological research has provided abundant evidence to show that the distribution of sea and land have been widely different in past ages to what it is now. Although these changes are exceedingly gradual, the periodic occurrence of earthquakes, followed by marked displacements of the land, reminds us that earth-movements can occasionally be both sudden and severe.

The most casual observers have noticed that the rocks of various areas exhibit marked differences of structure. In one locality, hard masses of a coarse granite may be seen over a wide extent of country; the rock may show no sign of stratification or of disturbance, and occupy an irregular-shaped tract. In a second region, the predominant rocks may be clearly banded gneisses and schists; the bands of these metamorphic rocks may be considerably twisted or folded. In a third region, flat-lying layers or beds of limestone, or shale, or sandstones may occur.

Folding.—Although the sedimentary rocks were originally deposited in a more or less horizontal position, it is nevertheless of common occurrence to find these beds in tilted and obviously disturbed positions. The condition of some of these buckled strata indicate that enormous compressional and shear stresses must have been the cause of the plication. These stresses are ascribed to the great forces which must become operative when regional elevation and depression take place. Massive, bedded rocks, like hard sandstones, are occasionally found arched in huge flexures with spans sometimes more than a mile across. Thinner or softer limestone beds are often seen buckled into folds of only a few yards each. Finely laminated strata, such as shales, may be exposed, in which the wrinkling is so close that the plications are measurable in inches. In section, these

PHOTOGRAPH V.



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OVER-FOLDED UPPER TRIAS STRATA. NORTH SIDE OF THE MANIRANG HIMALAYA.

PHOTOGRAPH VI.

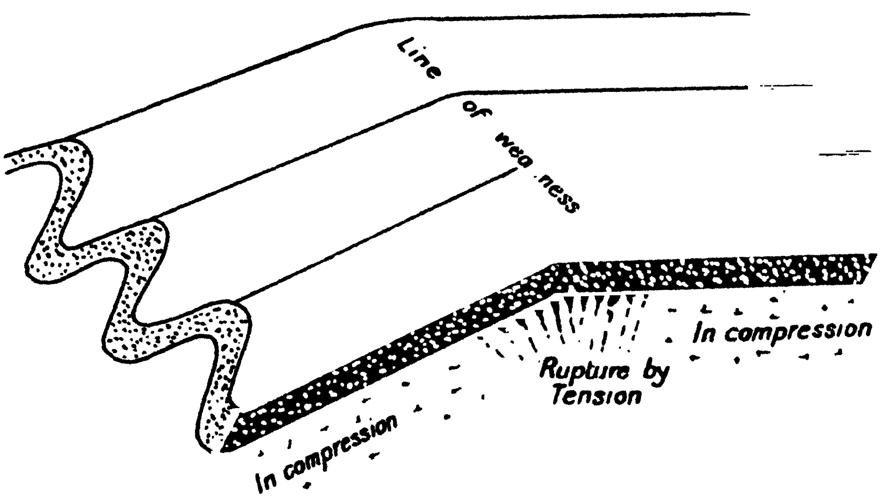
With the permission of D. G. S. I.] [*Photo by Sir H. H. Hayden.*

FOLDED JURASSIC STRATA. FOUR MILES W. BY S. OF GYANTSE, TIBET.

folds look like solid waves, each with its arch or anticline and corresponding trough or syncline. Some folds have the outline of regular sine-curves, others are inclined or over-folded, while the folds in mountain regions may be more complicated.

Rocks which have been involved in severe earth-movements are always affected by the resulting static pressures and dynamic forces to which they have been subjected in such movements. Some rocks, although showing the effects of the strain more clearly than others, are also more easily distinguishable in the complicated structure of a folded region. As a rule, in such areas, the complexities of individual sedimentary beds can be traced more easily than any other kind of rock.

In intensely-folded rocks, it is not unusual to find the beds



BUCKLED CORRUGATIONS
(Folded Strata with Tectonic warp.)

FIG. 42.

Shows closely folded strata which have been bent by a transverse warp.

thicker in the arches (anticlines) and troughs (synclines), and thinner in the limbs of the folds. Further, the rocks in the outer parts of the anticlinal and synclinal folds are frequently broken as though as a result of the tension in bending. The rocks in the inner parts of the arch and trough of the folds are either crushed or tightly compressed. In the limbs of the folds, on the other hand, shear forces have developed and caused the mineral grains of the rock to be pushed or thrust over each other.

Folded rocks are generally well exposed in true mountain ranges; and in these regions it is usual to find the valleys which

whereas the ridges and line of highest peaks overlie synclinal (trough) folds (see Fig. 6), the explanation being that the rock *on* the arch was broken and easily eroded, while the rock *in* the trough was tightly packed and therefore more resistant.

Parallel folds, besides producing a corrugated structure, indicate an enormous shrinkage of the superficial extent of the original horizontal rocks into those folds. On the Tibetan side of the Himalayas, north of Mount Everest, there is a wide spread of Jurassic rocks. These beds are folded parallel to the main range, and although the width of the exposed rocks is at least seventy miles, the length involved in the folding probably represents three times this amount. Occasionally the corrugated folds are warped or bent transversely (see Fig. 42).

Sometimes the rocks of a folded region are bent into a trough or arched. The axis of such a flexure is often parallel to the axis of the folds. (The structures thus formed are shown in Figs. 7

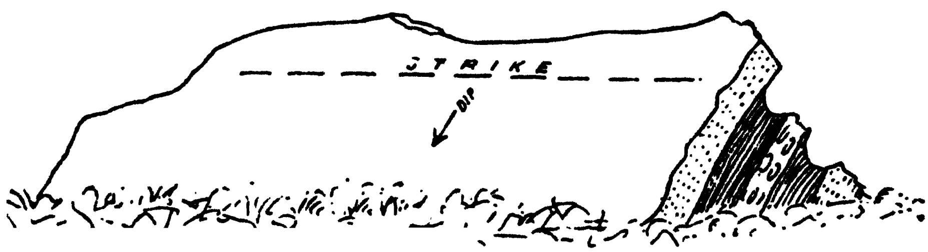


FIG. 43.

An out-crop of strata showing the direction of dip and strike of the beds.

and 8.) The trough structure is called a synclinorium and the arch structure an anticlinorium.

Strike and Dip.—In recording the tilt or slope of bedded or foliated rocks it is usual to make all measurements with reference to a horizontal plane. The same is true with regard to fault planes and cleavage joints (see Fig. 43). The direction or strike of a bed, fault or joint is the bearing of the line which a horizontal plane makes with the plane of the bed, fault or joint. The slope or dip of a bed or fault plane is the maximum angle, at a given locality, which the bedding plane makes with a horizontal plane. The direction of dip is always at right angles to the strike at the same place, but, as the dip may be in one or other of two opposite directions, particular care should be taken in stating the actual direction.

The width of out-crop of a given bed depends largely on the dip of the bed—thus, in Fig. 6, W_1 is greater than W_2 for the same bed, because the rocks are more steeply inclined in the latter position. Similarly the inclination of the ground modifies

PHOTOGRAPH VII.

With the permission of D. G. S. I.] *[Photo by Sir T. H. Holland.*

INTENSELY FOLDED LIMESTONES AND SHALES. LAHOUL, PUNJAB HIMALAYA.

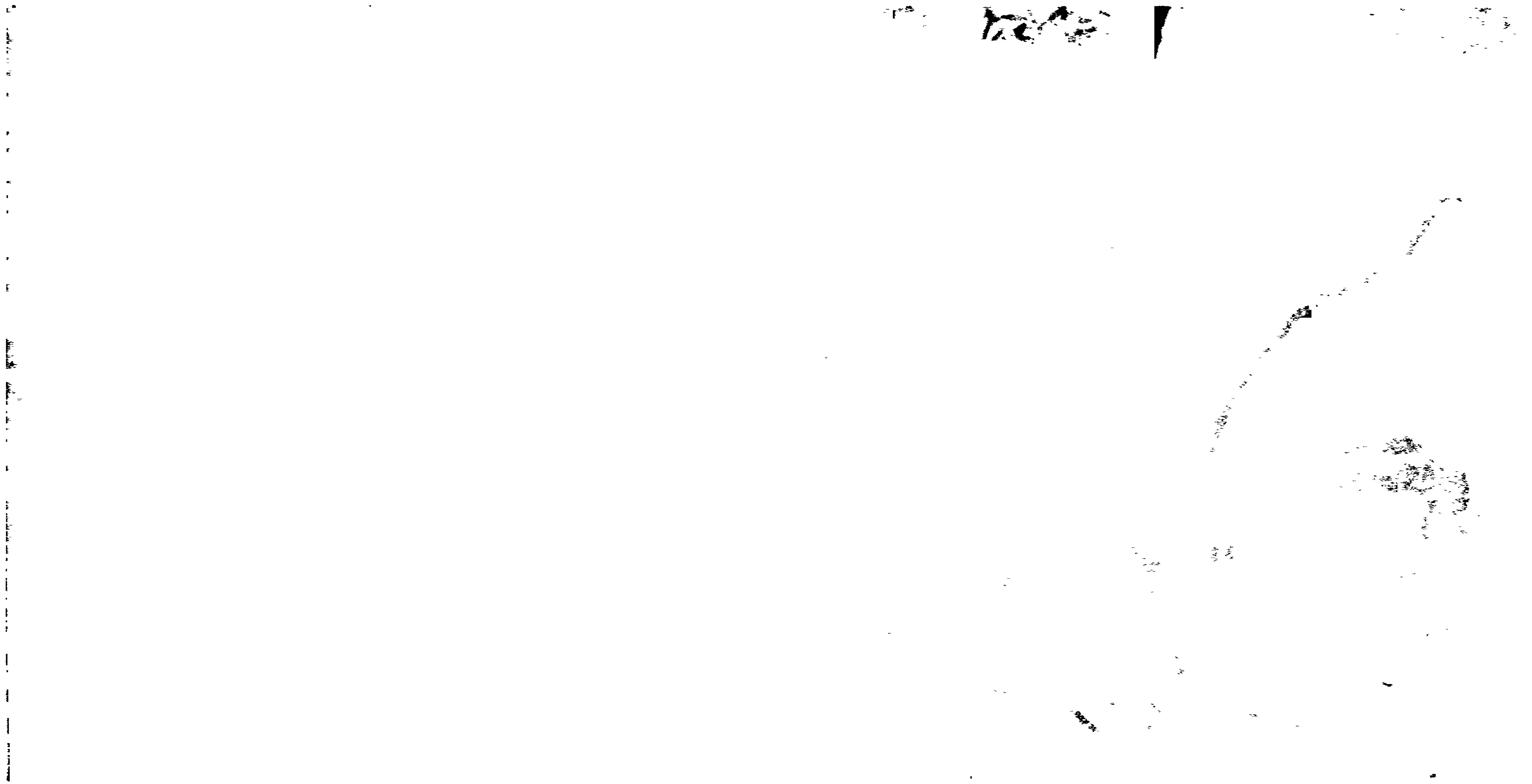
the width of an out-crop—thus, W_1 is greater than W_3, although the beds are the same and have equal dips. The ground surface at W_1 is less steeply inclined than at W_3.

Foliation Planes.—The foliation planes of the banded metamorphic rocks, such as the schists and gneisses, can be treated for purposes of measuring their strikes and dips in the same way as the bedding planes of the sedimentary rocks. If traced for some distance along their strike, these banded rocks either show lenticular structures or the banding appears to continue although the composition of the band alters. The gneisses and schists sometimes contain small or large inclusions (intrusions ?) of lens-shaped, lenticular-sectioned, very coarse-grained granitic rocks. These intrusive lenses are known as pegmatites. In some places these pegmatites are found in particular zones of the banding, and in other places they are seen to cross the lines of banding in an irregular manner. It is for this reason that they are thought to be intrusive into the banded rocks, and are commonly classed as igneous rocks of a particular type.

Ash Beds and Lava Flows.—True igneous rocks have several modes of occurrence. If they are extruded from deep within the earth's crust to the surface, they may quietly overflow the country as lava, or they may be ejected with explosive violence and be blown to pumice and dust (ashes). In the former case, they may flow far from their point of outflow, and resemble, when solidified, horizontal-lying, massive, sedimentary beds. In the latter case, they are thickest near the vent of the volcano from which they were ejected.

Dikes, Sills and Bosses.—Igneous rocks are pushed upwards through the overlying beds in variously shaped channels. In some cases the molten matter is forced upwards across the superincumbent strata in sheet-like channels. When the molten matter becomes solid in these channels, the resulting rocks are called dikes. If, however, the molten rock forces its way between two gently inclined sedimentary beds, the solidified igneous rock in this channel is called a sill. If a sill is lens-shaped it is called a lacolite. Should the molten mass force its way upward in a comparatively small circular-sectioned pipe, then the igneous rock which remains in the duct is spoken of as a plug or neck. If the plug is blunt towards the top and is of enormous dimensions, it may be called a boss or batholith. In most mountain ranges it is usual to find a granitic core parallel to the orographic axis of the range. It is thought by some geologists that an enormous dike-like boss has pushed up into the range. This view is questioned by other observers who think that the granite

PHOTOGRAPH VIII.



With the permission of D. G. S. I.] *[Photo by Mr. H. C. Jones.*

F U TED NIMAR SANDSTONE. URI RIVER, N. OF MANGARDA, AMJHERA DISTRICT, GWALIOR STATE.

core may be underlaid by sedimentary or metamorphic rocks (as shown in Fig. 8). In this case, it is thought that enormous static pressure has induced a re-crystallisation of other rocks and as a result produced a granitoid rock.

Faults.—When hard, massive beds of rock are subjected to great earth strain, they may show no sign of disturbance. When the strain finally exceeds the cohesive force within the

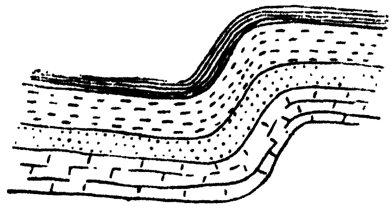
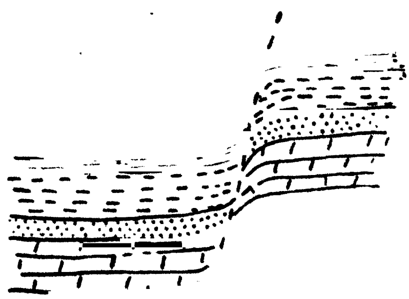


FIG. 44.
A monoclinal fold.

rock, a sudden fracture invariably takes place. This rupture is normally accompanied by a relative displacement of the strata on each side of the zone of fracture. The direction of the displacement of the rock on the two sides of a fault may be up or down, or laterally, or diagonally in the plane of the fault. These faults or fractures generally traverse the rocks in straight lines. The plane of faulting in most cases is steeply inclined—as shown in the following examples (see Figs. 44 to 48).

In a normal fault, the beds on one side appear to have been



45.
A normal fault.

let down by shearing or tearing. Step faults are a series of parallel normal faults. Trough faults generally mark a strip of rock which has been let down between two normal faults which face each other. In a reverse fault, the rocks appear to have been subject to compression and thus forced over each other. Thrust faulting is similar to reverse faulting in action, except that the fault plane is *not steeply* inclined. The several kinds of

faulting which are commonly met with are shown in Figs. 45 to 48, and they are closely related to some types of folds. Generally it is seen that the softer rocks, or those which become plastic

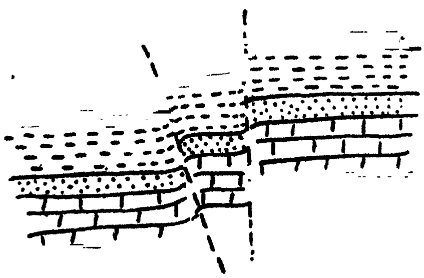


FIG. 46.
"Step" faulting.

under great earth-pressure, suffer without breaking; whereas the hard beds are suddenly snapped or sheared across. In some cases faults have been traced along their strike and found to

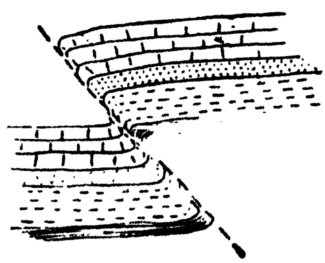


FIG. 47.
A "reverse" fault.

merge into a tectonic fold. Other instances are known in which the amount of dislocation of the beds on each side of a fault is less and less in one or other strike direction, until finally the fault

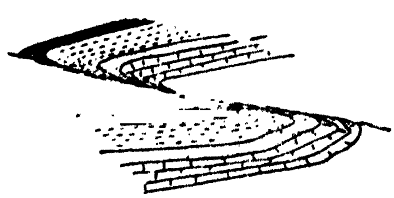


FIG. 48.
"thrust" fault.

is found to die out and the strata may be quite undisturbed. Fault planes remain zones of weakness in the rocks. In some regions, where earth-movements are in progress, a fault

may often act as a "safety valve" for the relief of strain. Small, sudden, relative movements of the rock take place from time to time in the plane of faulting. These earth-tremors may not be felt or cause alarm or destruction, although they may be detected by sensitive instruments of special construction. Under similar circumstances, the fracturing of massive, unbroken rocks might, when the accumulated strain had exceeded the power of resistance of the strata, produce terrible, world-shaking earthquakes.

In locating the sites of important engineering structures, such as dams, the line of a fault should be carefully avoided. Earth-movements are generally least active in regions of very ancient crystalline rocks (i.e. granitoid gneisses and schists, etc.). In such areas, it is not uncommon to find that the fault fissure has become filled or cemented up with mineral deposits. The "old fault" has become "dead," and its mineralised condition, besides perhaps constituting a valuable mineral vein, may render the old plane of dislocation as strong as the unbroken rock.

When unconsolidated rocks, such as soft sandstones, etc., are faulted, the relief of strain is not as a rule adjusted by further slip movements in the plane of the fault. Pressure merely adds to the tendency to consolidate the beds. Earth-movements or earthquake tremors are therefore absorbed or deadened by a kind of cushioning action in such strata. Consequently a certain degree of liberty is permissible when dealing with the new groups of rocks in the earth's crust (from those of Cretaceous age upwards).

Joints.—The divisional planes or cleavage cracks or joint fissures which are so common in all large masses of rock are miniature faults. They are indicative of shrinkage by compression or contraction. When a molten mass, such as a basaltic lava flow, cools and solidifies, an enormous amount of contraction takes place. The stress which accompanies this contraction develops a strain beyond the elastic limits of the rock, and produces a series of more or less regularly-spaced joints. The almost perfect columnar structure seen at the Giant's Causeway in Co. Antrim (Ireland), and at several other places in various parts of the world, are examples of contraction joints of this type (see Fig. 49). If, on the other hand, a uniform mass of unconsolidated material is subjected to enormous pressure, it will be compressed and occupy a smaller volume, and joint planes will develop at more or less regularly-spaced intervals (see Fig. 50). Should the partially consolidated material be finally forced down to a great depth in the crust of the earth and exposed to moderately high temperatures under immense pressure a further

diminution in volume will possibly occur. The component mineral particles will not only pack more closely together, but their molecules will do the same and recrystallise as denser

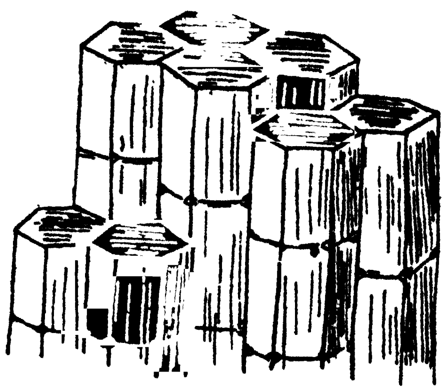


FIG. 49.

Prismatic or columnar jointing.

minerals, and thus produce heavier and more compact rocks. This diminution in volume under pressure induces a condition of strain which is only relieved by the production of divisional planes of weakness, such as joint planes, or cleavage (see Fig. 51).

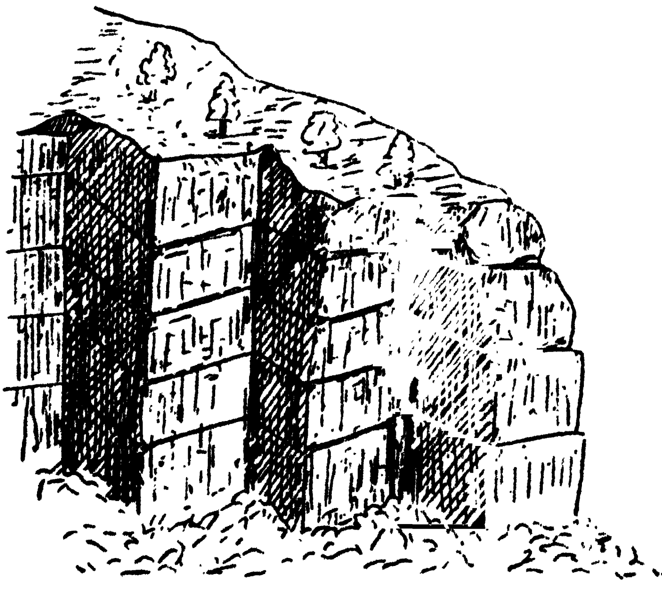


FIG. 50.

Shows the typical jointing of massive rocks.

These planes of weakness may not be clearly visible in fresh, undecomposed rocks, though they are evident in weathered specimens. They can, however, be utilised in quarrying the rock.

It has been found, when other conditions are similar, that the texture of a rock affects the distances between successive parallel joint or cleavage planes. In coarse-grained granites the individual blocks which can be obtained from one group of joints may be of gigantic size. Enormous slabs have often been quarried from hard, coarse-grained, massive sandstones. It is difficult to obtain very large blocks from quarries in fine-textured rocks, such as basalt, quartzite and some marbles. The thin sheets of very fine-textured clay-rock, known as slate, are familiar enough to all engineers.

There are usually three sets of joints or parting in all rock masses. In most rocks the three sets of divisional planes are, more or less, at right angles to each other. If the rocks are

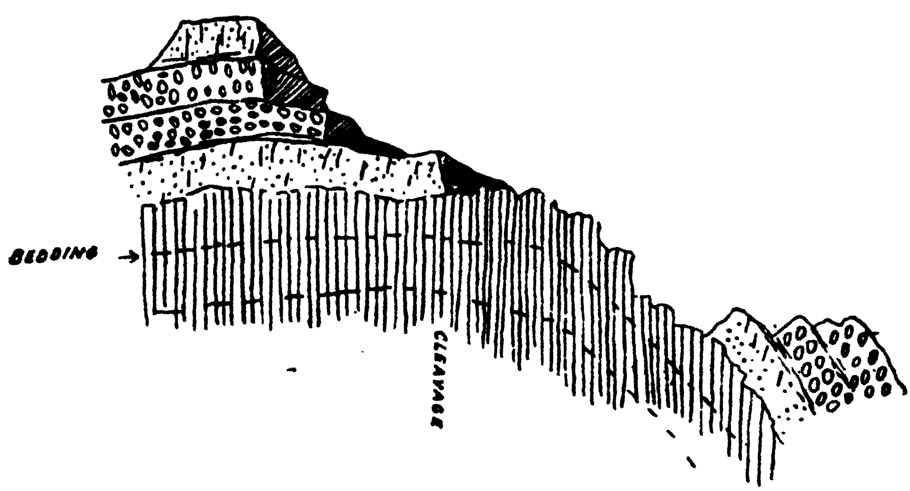
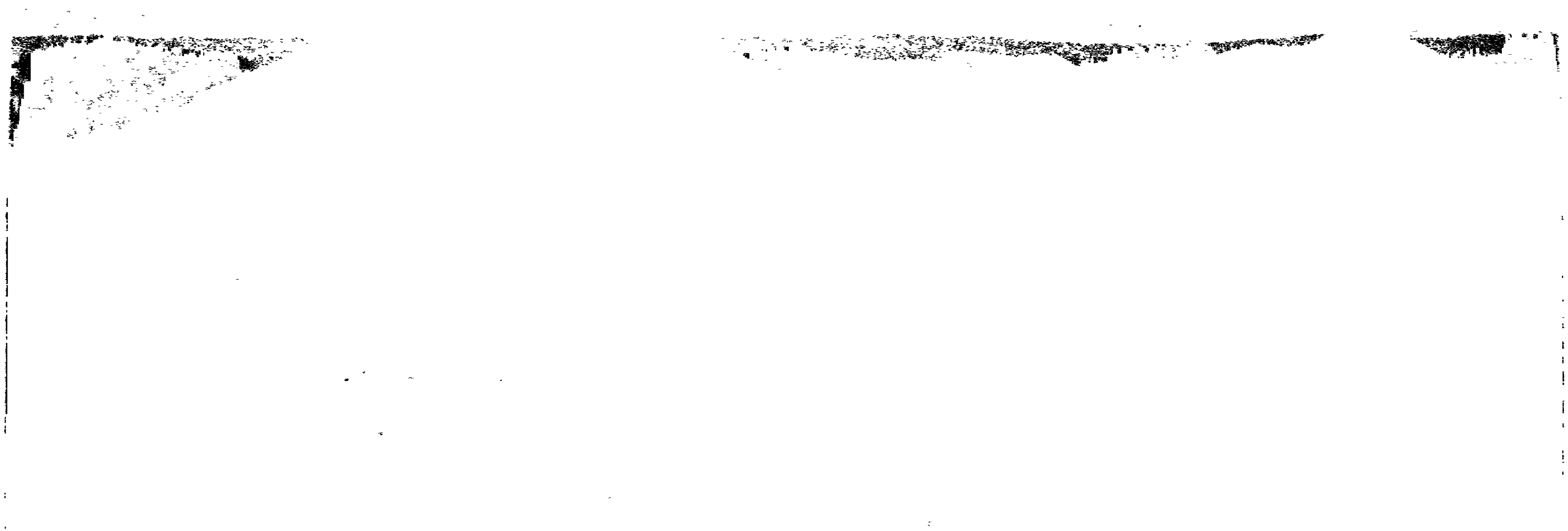


FIG. 51.

Shows the cleavage of the slates perpendicular to the bedding. All the beds shown are conformable, but they have been subjected to an intense compression normal to the cleavage plane.

bedded, as in the case of the sedimentary rocks, the bedding plane will function as one plane of parting. When such beds are tilted, the joint planes may be vertical, and therefore oblique to the inclined bedding plane. In the case of beds which dip at various angles, one set of vertical joint planes generally occur parallel to the strike of the beds and are called "strike joints"; a second set of vertical joint planes, usually not so well developed, cut the beds in the direction of their dip and are called the "dip joints." Cases occur, particularly where the strata have been severely buckled and compressed, in which the strike and dip joints are absent and two sets of diagonal joints are present. If these rocks have been subjected to intense compression, it may be impossible to obtain large-sized blocks for building

PHOTOGRAPH IX.



With the permission of D. G. S. I.] [*Photo by Dr. L. L. Fermor.*

LATERITE CAPPED PLATEAU ON HORIZONTALLY BEDDED BASALTIC LAVAS. PANCHGANI, NEAR MAHABLESHWAR, BOMBAY PRESIDENCY.

purposes, because, although large pieces may be quarried, they break up too easily when handled and trimmed.

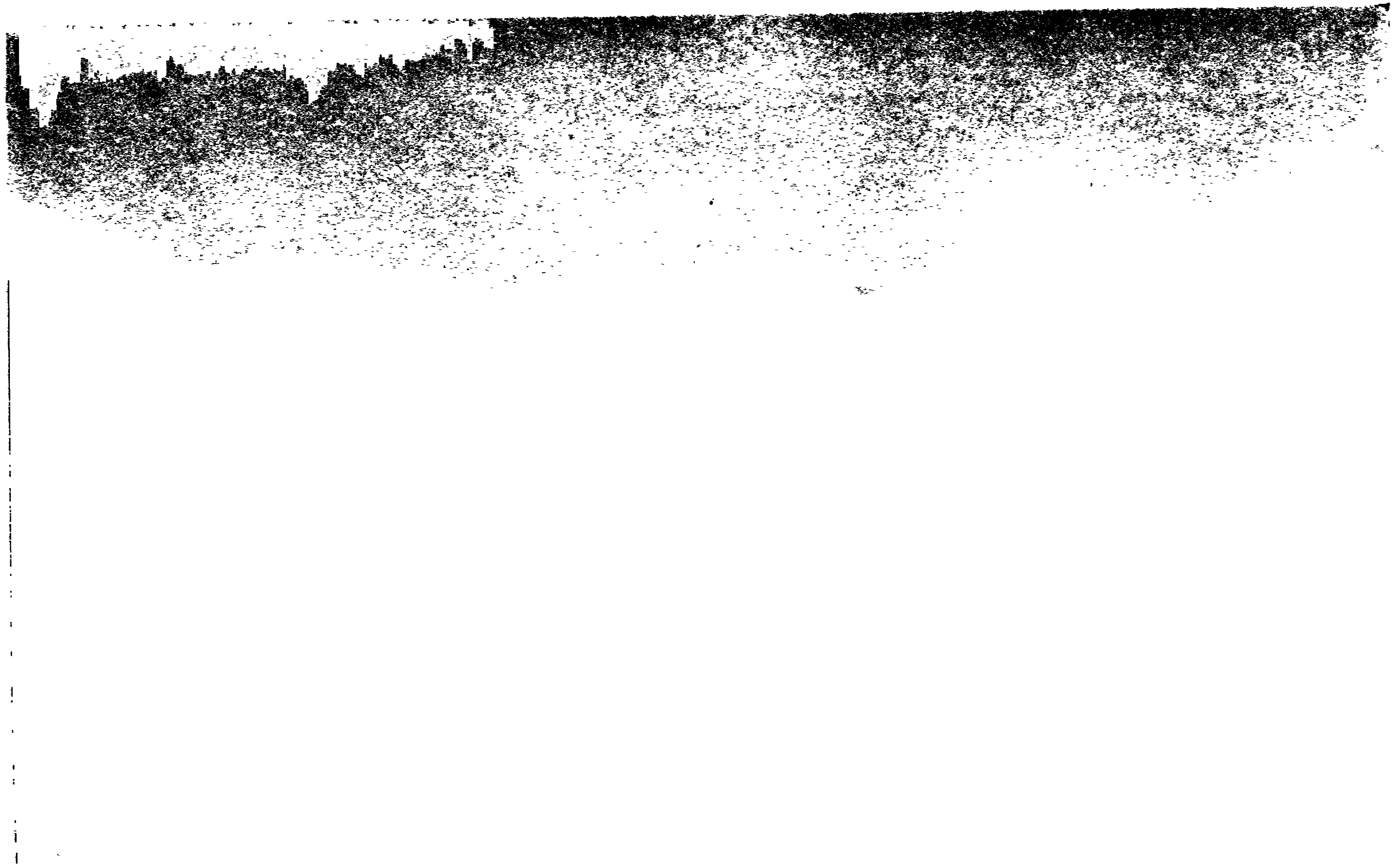
Geological Maps.—If the surface of a country was stripped of all vegetation and soil and the rock laid bare, it would be possible, with sufficient expenditure of time and money, to colour the different kinds of rock in a distinctive way, e.g. sandstones yellow, shales grey, limestones blue, granites pink, dolerites green, etc., etc., and to mark the position of inclined strata and other structural details with suitable signs. An observer in an aeroplane looking down on such a surface would see a real geological map.

An ordinary map, with the topographical features clearly shown, forms the basis of a geological map. On it the geologist marks the position of the out-crops, dips, faults, etc., of the rocks which occur in the area of the map. If the geological details are intricate, he requires a smaller scale map, just as an engineer would do to show the contours of a reservoir basin. If the direction and degree of the dips and faults, etc., are accurately delineated, the map will serve as a plan from which cross-sections can be constructed. By so doing it is possible to depict the solid structure of the rocks of any area, and *vice versa*, by studying a geological map and geological sections, it should be possible to obtain an idea of the structure of the country which the map depicts.

The geological maps published by the Geological Survey of Great Britain are of two kinds—Solid maps and Drift maps. The former type resembles the map described in the preceding paragraph. They do not show superficial accumulations such as glacial drift, etc. In the latter type of map these omissions are inserted. Drift maps are of importance in surface works—such as reservoir sites, the location of dams, etc. Solid maps are useful in questions of mining, boring, etc., when the work lies some depth below the surface.

There are certain details shown on carefully prepared geological maps from which it is possible to draw correct conclusions regarding the geological structure, in the same way as an engineer can read into the surface features of a country from an accurate topographical map. For example, when contour lines are seen close together on a topographical map it is safe to infer that the slope of the ground is steeper there than in an area where the contours are further apart. Similarly, on geological maps, gently inclined strata show wide out-crops on level ground and narrow out-crops on steep slopes. The out-crops of horizontal beds will curve into the valleys with the contours. Also beds which cross a valley transversely and dip

PHOTOGRAPH X.



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up-stream will have in-baying out-crops. If these out-crops go far up the valley it means the strata have gentle dips. On the other hand, if the in-baying is slight the inference is that the beds are dipping at a high angle. Should the out-crops cross the valley in straight lines it is obvious that the strata must be vertical. When the out-crop of a group of beds is represented by a V, with the point of the V down the valley, it is generally safe to conclude that the strata are dipping down-stream. If the beds cross a valley obliquely or are folded irregular out-crops will be shown.

For reasons of uniformity in the production of geological maps, it is best to choose the same colours for representing rocks and the same symbols or signs for indicating dips, etc., as have been adopted by the geological survey of the country in which investigations are being made. The index of colours and signs is always attached to a geological map, as it forms a key to the interpretation thereof.

An engineer is often able to lay down the general alignment of a railway on a good topographical map without having previously gone over the ground. Similarly, with an accurate geological map, it is possible for a geologist to estimate the depth at which certain beds of rock may be encountered in sinking a well. The making of maps and the drawing of sections are so essential a part of the engineer's work that he will seldom have any difficulty in reading a geological map. Also, if he is familiar with the common rocks and can unravel the structure of an area, he will, with his greater experience, be able to produce a very neat, mechanically correct, geological map.

CHAPTER II

THE PRINCIPAL ROCK GROUPS

ALTHOUGH a rock may be defined as an aggregate of minerals, the term is more specifically applied to those mineral aggregates which form an essential part of the earth's crust. It is necessary, in this sense, that all rocks must possess certain individual characteristics by which they can be easily recognised. Numerous mineral aggregates, such as the various metalliferous ores, etc., although important from a metallurgical or economic point of view, constitute a very insignificant part of the rocky portion of the globe. They are therefore, strictly speaking, not rocks. In other cases it is more difficult to decide ; as a rule, however, it is undesirable to elaborate the subdivisions of the chief rock groups.

There are three great classes into which it is usual to group the various types of rock which have been recognised on the crust of the earth :—

(1) Igneous rocks, or those which have solidified from a molten condition ;
(2) Sedimentary rocks, or those which have derived their material from pre-existing rocks ; and
(3) Metamorphic rocks, i.e. those which, as their name indicates, are changed or modified varieties of the preceding classes.

Each of these great classes is again capable of much subdivision into families, etc., depending on their mode of occurrence and chemical or mineralogical composition, as shown in the accompanying table of classification (see Folding Plate).

A Classification of Rocks.—The arrangement of vertical and horizontal divisions shown on the accompanying scheme of classification (see Folding Plate) are intended to represent portions of a section of part of the earth's crust. The top horizontal set of divisions, 1 to 20, are supposed to be part of the earth's surface. On the extreme left, divisions 1 to 5, there is an imaginary mountain range in which only igneous rocks occur. In the middle, divisions 6 to 14, there are supposed to be deposits

of sedimentary material which have been laid down by eastward (to the right) flowing streams which drain the hypothetical mountain tract. The coarse debris naturally accumulates near the mountains, whilst the fine, suspended mud and the soluble constituents are swept into the sea. On the extreme right, divisions 15 to 20, there are the important surface accumulations.

The successive divisions, downwards, A, B, C, D, E and F, represent zones—one below the other—from the surface into the depths of the earth ; thus :—

Zone A is the surface of the ground on which deposition takes place.

Zone B includes all rocks which have been formed at the surface, such as ash beds, lava flows, soft sandstones, etc., and are either actually exposed at the surface of the earth or lie above the level of the stationary ground water.

Zone C extends from near the surface to a considerable depth. In it the rocks, although subject to heavy earth pressure, are not exposed to high temperatures; unconsolidated beds are more or less consolidated, and the whole zone is probably below the level of the stationary ground water. Dikes and sills and lacoliths of the igneous rocks occur in this zone in intrusive relationship with older rocks.

Zone D is at a great depth from the surface. No open fissures can exist at this depth, because the pressure is sufficient to cause even the hardest rocks to " flow." The temperature range in this zone, although possibly above 365° C., the critical temperature of water, does not extend to the melting-point of the rocks. Great masses of granite and other igneous rocks are associated with this zone. The sedimentary rocks become thoroughly consolidated under the enormous pressure to which they are subjected at this depth.

Zone E represents the dynamic aspect of zone D. Both are at approximately the same depth. When no earth-movements are operative, the conditions of zone D exist ; but when immense tectonic forces—of compression and torsion and shear—act on the somewhat pliable rock, distortion takes place. Igneous rocks, like granites, etc., are rendered gneissose ; schistosity is developed ; sedimentary rocks are converted into their metamorphic equivalents, and quartzites, phyllites, marbles, etc., are formed.

Zone F. Zones D and E pass downward into a zone subject to enormous pressures and very high temperatures. The rocks are thought to be in a semi-plastic condition. When merely static pressures prevail, the rocks crystallise with coarse granitic textures.

Zone G is considered to be an extreme condition of zone F.

The prevailing pressure and temperature is presumed to be so high that a release of pressure in any part of this zone immediately results in a liquefaction of the plastic rocks in that region. This zone constitutes the petrological melting-pot for all rocks. Dr. Fermor has designated it the infra-plutonic zone.

A careful examination of the classification will enable most people to trace the history and mode of formation of the commoner types of rock which are met with in engineering operations.

Relative Proportions of the Various Rocks.—It is impossible to estimate the proportions of the various types of rock. Various approximations have been made, and these results are summarised in the table below :—

Igneous rocks	A. Acid types	63 %	95 %	These include their metamorphic representations.
	B. Basic types	32 %		
Sedimentary rocks	C. Shales	4 %	5 %	
	D. Sandstones	0·75 %		
	E. Limestones	0·25 %		

(N.B.—See chemical analyses below.)

It is seen from this analysis how large a part of the earth's surface consists of acid igneous rocks, the total proportion of all the igneous rocks being no less than 95 per cent. of the whole.

Chemical Composition of the Various Rocks.—Dr. F. W. Clarke (*Data of Geo-Chemistry*, Bull. No. 330, p. 261, U.S. Geological Survey) estimates that the chemical composition of these various types of rock are shown as below :—

	A and B.	C.	D.	E.	Average of Whole.
Silica	59·87	58·10	78·33	5·19	59·79
Alumina	15·02	15·04	4·77	0·81	14·92
Ferric oxide	2·58	4·02	1·07	0·54	2·63
Ferrous oxide	3·40	2·45	0·30	—	3·33
Magnesia	4·06	2·44	1·16	7·89	3·98
Lime	4·79	3·11	5·50	42·57	4·82
Soda	3·39	1·30	0·45	0·05	3·28
Potash	2·93	3·24	1·31	0·33	2·96
Water	1·86	5·00	1·63	0·77	1·98
Titanium oxide	0·72	0·65	0·25	0·06	0·71
Zirconium oxide	0·03	—	—	—	0·03
Carbon dioxide	0·52	2·63	5·03	41·54	0·74
Phosphorous pentoxide ..	0·26	0·17	0·08	0·04	0·25
Sulphur	0·11	—	—	0·09	0·10
Chlorine	0·42	1·49	0·12	0·12	0·44
Total = With other constituents.	100	100	100	100	100

An average chemical analysis of the various groups of the igneous rocks is shown below. These values do not give any idea of the great variations in composition which are frequently found in certain types of each of the groups.

	1.	2.			5.
Silica	71·0	62·0	58·0	47·0	40·0
Alumina	15·0	20·0	18·0	16·0	6·0
Ferric oxide ..	1·0	1·0	2·7	3·0	5·0
Ferrous oxide ..	1·0	1·7	3·8	8·0	8·0
Magnesia	0·7	0·8	2·5	8·5	32·0
Lime	1·4	1·6	5·8	12·0	6·0
Soda	3·5	5·3	3·7	2·0	0·5
Potash	5·0	5·0	2·5	0·8	0·5
Other constituents ..	1·4	2·6	3·0	2·7	2·0
Total	100	100	100	100	100

1. Acid group.
2. Acid intermediate group.
3. Basic intermediate group.
4. Basic group.
5. Ultra basic group.

Details of the composition of the sedimentary rocks are given in the previous table. The composition of the metamorphic rocks (except certain peculiar residual types such as laterite, or special varieties such as coal) are similar to the rocks—igneous or sedimentary—which have been metamorphosed.

Mineral Composition of the Rocks:—Rough guesses, based on some determinative work, have been made regarding the importance and relative proportions (by weight) of the minerals which compose the rocks of the earth's crust. The most recent of these (*Economic Aspects of Geology*, by C. K. Leith) gives the following percentages :—

	Per cent.
1. Felspars	49
2. Quartz	21
3. Augite, hornblende and olivine	15
4. Mica	8
5. Magnetite	3
6. Titanite and ilmenite	1
7. Kaolin, limonite, dolomite, hematite, calcite, gypsum, etc.	3
	100

The same authority estimates the following percentages of various minerals in the igneous rocks :—

	Per cent.
1. Felspar	50
2. Quartz	21
3. Augite, hornblende and olivine	17
4. Mica	8
5. Magnetite	3
6. Titanite	1
	100

And the following percentages of various minerals in the sedimentary rocks :—

	Per cent.
1. Quartz	35
2. Felspar	16
3. White mica	15
4. Kaolin	9
5. Dolomite	9
6. Chlorite	5
7. Calcite	4
8. Limonite	4
9. Gypsum, carbon, apatite, rutile, magnetite, zircon, etc.	3
	100

THE IGNEOUS ROCKS.

The igneous rocks (see divisions 1 to 5 in the accompanying classification) are usually subdivided into several groups or families : (1) The Acid group, or Granite-rhyolite family ; (2) the Acid intermediate group, or Syenite-trachyte family ; (3) the Basic intermediate group, or Diorite-andesite family ; (4) the Basic group, or the Dolorite family ; and (5) the Ultra-basic group, or Peridotite, etc., family. This arrangement depends largely on the composition of the rocks, i.e. the relative quantities of acid (silica, etc.) and basic constituents (iron, magnesium, etc.) which they contain. These groups are next classified as Volcanic, Hypabysal and Plutonic varieties, according to their superficial or deep-seated origin. The acid varieties generally contain pale-coloured minerals, quartz and felspar, and are consequently pale-coloured in appearance. The basic varieties contain large amounts of augite, hornblende, olivine, etc., frequently with—but sometimes without—felspar, and are dark in colour. All the plutonic, and most of the hypabysal, types consist entirely of interlocked or interlaced crystals. They are wholly (or holo-) crystalline. Some hypabysal and many volcanic rocks contain a matrix of volcanic

glass with large, individual crystals. They are said to have a porphyritic texture. Among the volcanic rocks greater differences exist. Certain kinds contain steam holes or vesicles (vesicular), others have the porous structure of pumice, while some varieties are fragmental, such as volcanic ash, and others are wholly of volcanic glass.

Except for the vesicular and fragmental types, most igneous rocks when undecomposed have an impervious texture and do not usually absorb water. Their water-containing capacity

By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 1.

Fine-grained porphyritic basalt.
(Magnification 25 diameters.)

normally depends on the cracks and joints which traverse these rocks.

Texture (Coarse- to Fine-Grained), Granular, Porphyritic and Ophitic.—The types of deep-seated origin are generally coarse-grained, while those which have been chilled may have medium- to fine-grained textures. This difference of texture is very well illustrated by the following series of photographs of the microscope sections of a dolerite dike. The specimens were collected from a dike in the Chhindwara District of the Central Provinces of India.

No. 1 (Reg. No. 822) was taken from the margin of the dike

at its contact with gneiss. The photomicrograph (magnification 25 times in all these photographs) shows long (phenocrysts) crystals of plagioclase felspar in a ground mass of augite and volcanic glass.

No. 2 (Reg. No. 823) was collected 1 foot away from the contact. The same minerals are seen. This rock would make excellent road metal. It is a typical basalt.

No. 3 (Reg. No. 824) was obtained 2 feet away from the plane of contact. There is less interstitial volcanic glass and

By favour of I E. I.] [*C. S. F.*

PHOTOMICROGRAPH 2.

Porphyritic basalt. (× 25 dia.)

the texture is coarse. It would be suitable for road metal and for paving setts. It has the texture of a doleritic basalt.

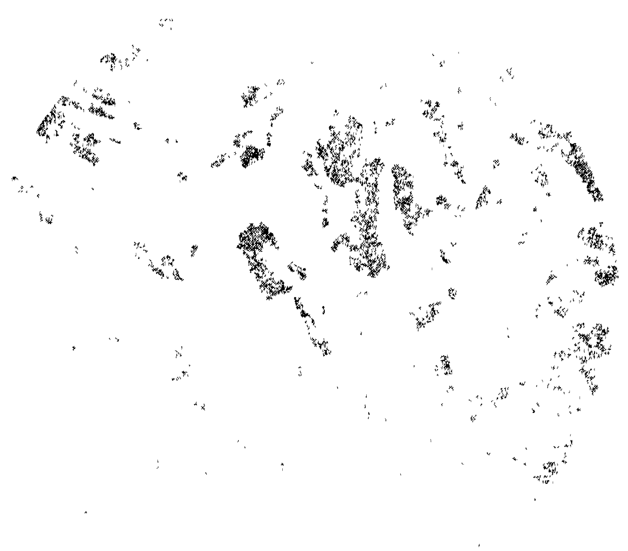
No. 4 (Reg. No. 825). A sample, collected 5 feet from contact, shows typical dolerite, with practically no glassy matter. It makes excellent setts and building stone, while the sharp fragments are useful for concrete.

No. 5 (Reg. No. 826). Specimen, taken from middle of dike (36 feet from contact), shows coarse, granitoid texture. There is no glassy matter. Some specks of magnetite are visible between the large interlocked crystals of plagioclase felspar and augite. It is coarse dolerite or gabbro. Owing to the great difference in the cubical expansion of plagioclase felspar and

augite (see section on rock-forming minerals), this rock would crumble if it were exposed to fire and then drenched with water.

In a later section, the influence of the shape, size and mineral composition of the component grains will be discussed. For the present, it is enough to say that when the grains are equal-sized and irregularly rounded the texture is said to be *granular*; when large crystals occur in a ground mass of smaller crystals the texture is said to be *porphyritic*; and when the component materials occur in tabular or needle-shaped forms, thoroughly interwoven or interlaced, the texture is said to be *ophitic*.

Granite generally has a granular texture (see Photomicro-



By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 3.

Typical doleritic basalt.
(× 25 dia.).

graph No. 15, Reg. No. 1069). In the photomicrographs described above, No. 1 (Reg. No. 822) shows a typical porphyritic texture, while No. 4 (Reg. No. 825) represents an excellent example of ophitic texture.

Acid Rocks.—Granite, granite porphyry, rhyolite represent the general family with their plutonic, hypabysal and volcanic types. The granites are usually coarse-grained, though they vary in texture. They generally consist of recognisable grains of quartz, orthoclase felspar and mica, either white or black or both. Many varieties occur in which hornblende or

other minerals may be present. The hypabysal forms—i.e. porphyry, etc.—are usually porphyritic in texture, though of the same general composition as granite. The volcanic representations—i.e. rhyolite, etc.—are either glassy or exceedingly fine-grained (crypto-crystalline) in texture.

The specific gravity of these rocks varies from 25·5 in the fine-texture types (rhyolites) to over 2·65 in granite. They weigh from 155 to nearly 175 lb. per cubic foot for solid blocks. The crushing strength averages 800 tons per square foot for fine-grained granite, 1,000 tons per square foot for

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PHOTOMICROGRAPH 4.

Ophitic-textured dolerite.

(× 25 dia.)

medium-grained types, and 700 tons per square foot for coarse-grained granites.

Granites with much visible quartz are particularly liable to disintegration when exposed to abnormal variations of temperature (see section on rock-forming minerals).

Acid Intermediate Rocks.—Syenite, porphyry, trachyte represent the plutonic, hypabysal and volcanic types of this group of rocks. They have very similar textures to those of the granite family. Quartz is seldom evident in visible grains; subsidiary minerals, on the other hand, are more frequently

present, and have several varieties—hornblende syenite, nepheline syenite, etc., are known. A cubic foot of syenite weighs, roughly, 170 lb., but the different kinds vary. The specific gravity varies from 2·60 to 2·72 or more. In strength the syenites are generally somewhat superior to granites of similar texture. Like the granites, these rocks can often be quarried in enormous blocks, owing to the great distances between the successive joints. The most readily decomposable mineral in both normal syenites and granites is the felspar. This decomposition is easily detected by an examination of a thin section

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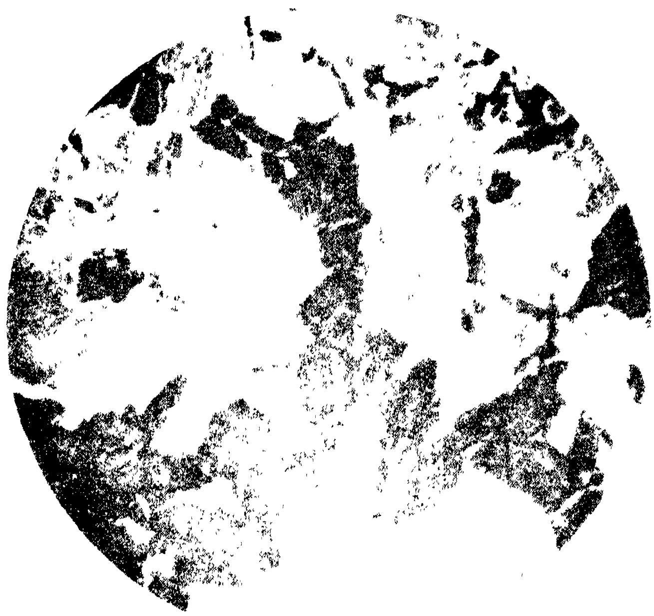
PHOTOMICROGRAPH 5.

Gabbro or coarse-textured dolerite.
(× 25 dia.)

under the microscope. Certain varieties, such as phonolite (clinkstone), are resonant when slabs of it are struck with a hammer. These rather finer-grained types make good paving stone because of their weathering qualities.

Basic Intermediate Rocks.—Diorite, porphyrite, andesite are respectively the deep-seated hypabysal and volcanic representatives of this family of rocks. They generally contain appreciable quantities of augite (pyroxene) or hornblende (amphibole), and very rarely show any trace of free grains of quartz (even under the microscope). Plagioclase felspar replaces the orthoclase felspar

of the more acid types. The texture varies from granular to porphyritic; the colour—owing to the ferro-magnesian minerals—is usually dark. The compressive strength of some of the medium-textured varieties of diorite is often as much as 1,500 tons per square foot (crushing). The specific gravity of diorite is, roughly, 2·85; and a cubic foot of the rock weighs 175 to 180 lb. Andesite, on the other hand, may have a specific gravity as low as 2·70. A cubic foot of this rock weighs from 165 to 172 lb. The various kinds of basic intermediate rocks are tough and durable, if the specimens chosen are undecomposed. The diorites



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PHOTOMICROGRAPH 6.

Altered dolerite (Diabase) showing the paramorphism of augite to hornblende. (× 25 dia.)

make good building stone and excellent paving stone and setts. The andesites are perhaps the best type of material for road metal—particularly in the old class of macadam road.

Basic Rocks.—Gabbro, dolerite, basalt. This family of rocks is commonly spoken of as trap. They are dark green to purple in colour; their texture and variation of grain were well shown in the photomicrographs already discussed. Plagioclase felspar and augite are the most conspicuous minerals; magnetite is frequently present; olivine is also a common component. These rocks are, however, subject to comparatively

rapid alteration; usually the felspar is decomposed and the augite undergoes a change as a result of which green hornblende is developed. In some cases a dolerite has been found to have been transformed by this paramorphism into an entirely different kind of rock—exactly the same in chemical composition but with quite different minerals. This is well shown in the following photomicrographs.

No. 6 (Reg. No. 828) gives an idea of a dolerite in the process of alteration (not decomposition) by recrystallisation. This phase is followed by the growth of needles of green hornblende

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PHOTOMICROGRAPH 7.

Typical epidiorite showing green hornblende and plagioclase felspar. (× 25 dia.)

on the margins of the augite and the development of the mineral apatite.

No. 7 (Reg. No. 830) shows a complete transformation of the augite into green hornblende. The felspar has also recrystallised into a more stable variety. The rock is a true epidiorite, because there is enough evidence to indicate its origin. It is uncommonly tough and strong.

No. 8 (Reg. No. 831) shows very clearly the growth of the green hornblende in accicular crystals. The augite has been entirely converted, and fresh felspar has also developed at the

expense of the original felspar. The rock is exceedingly tough and durable, and is known as an epidiorite. It is, however, not always possible to say if this rock is of secondary origin or an original diorite. The basalts make excellent road metal, because, by their alteration, secondary minerals develop which make the whole metalling more compact. Blocks of doleritic basalt, such as the Rowley Rag, have been long utilised as paving setts because of their toughness and resistance to abrasion. Dolerite also makes good paving stone, and is always a strong building stone; unlike the granitic rocks, which can be obtained in

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PHOTOMICROGRAPH 8.

An epidiorite with slender interpenetrating needles of green hornblende. (× 25 dia.)

monoliths of great size, it is usually difficult to quarry blocks of anything like the same proportions. The basic rocks are more heavily jointed by closer-spaced joints, possibly because of the greater contraction which takes place when the molten material solidifies. The average crushing strength of doleritic basalt is, roughly, 1,000 tons per square foot, some epidiorites being stronger. The specific gravity of these rocks varies from 2·90 to 3·10, or a little more. A block of a cubic foot weighs, approximately, from 175 to 185 lb. One word of warning is, however, necessary with regard to the use of basalt for road

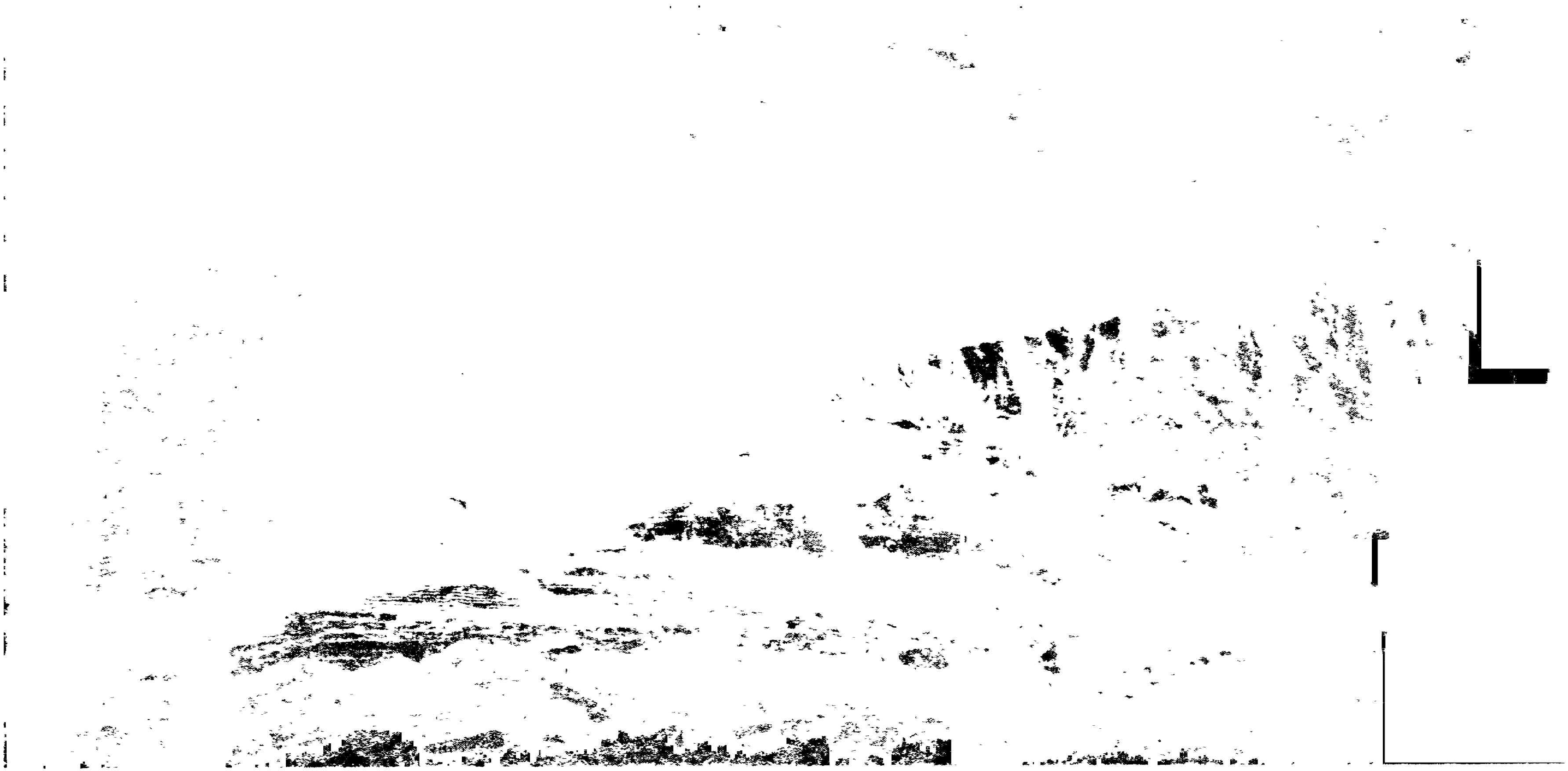
metal: badly-decomposed earthy trap is basalt, but it is not the strong material which has been discussed, consequently the same results cannot be obtained by using the soft-weathered material.

Ultra-basic Rocks.—Dunite, peridotite, limburgite. There is a dispute as to whether these three names refer to the rocks of plutonic, hypabysal and volcanic origin. The whole family is peculiar; some types consist almost entirely of augite or other pyroxene mineral, others are practically pure aggregations of olivine, while combinations of these are common, in some cases including plagioclase felspar. The texture is generally coarse ophitic. The rocks are liable to comparatively rapid decomposition when subject to prolonged weathering. They pass by paramorphism into serpentine, talcose and similar rocks of secondary origin. When fresh, some varieties are tough, but as they are not extensively used—except as ornamental stone, because of the beautiful play of colour which some polished specimens show—there is little reliable information regarding their crushing strength. The specific gravity varies from 3·00 to 3·30, and a cubic foot weighs on an average 180 to 190 lb.

THE SEDIMENTARY ROCKS.

The materials which compose sedimentary rocks have, in most cases, been deposited in a more or less horizontal position under water. The subsequent consolidation of the detrital material into beds of rock is generally effected by the weight of later deposits. The characteristic feature of the sedimentary rocks is their stratification; the several layers may be thin or thick, the resultant rock being laminated or bedded. A number of such beds may be conformably superposed, and thus constitute a series. In some cases, one such series may be found to overlie another series of rocks in an unconformable manner (see Photographs XI and XII). There is often, owing to conditions of depositions being different, a change in the composition of the beds when traced laterally. This difference of composition is more evident in the upward or downward section of a series of beds. Beds of coarse gravel may be overlaid by sandy layers, and these in turn may be covered by laminated clays, which pass upward into beds of limestone. Such a section would clearly indicate great geographical changes. The coarse gravels having been deposited by swift-flowing rivers, the clays probably settled in the quiet waters of a lake or sluggish river; while the limestone would suggest that the area finally sank beneath the sea. The individual grains which compose the materials of most sedimentary

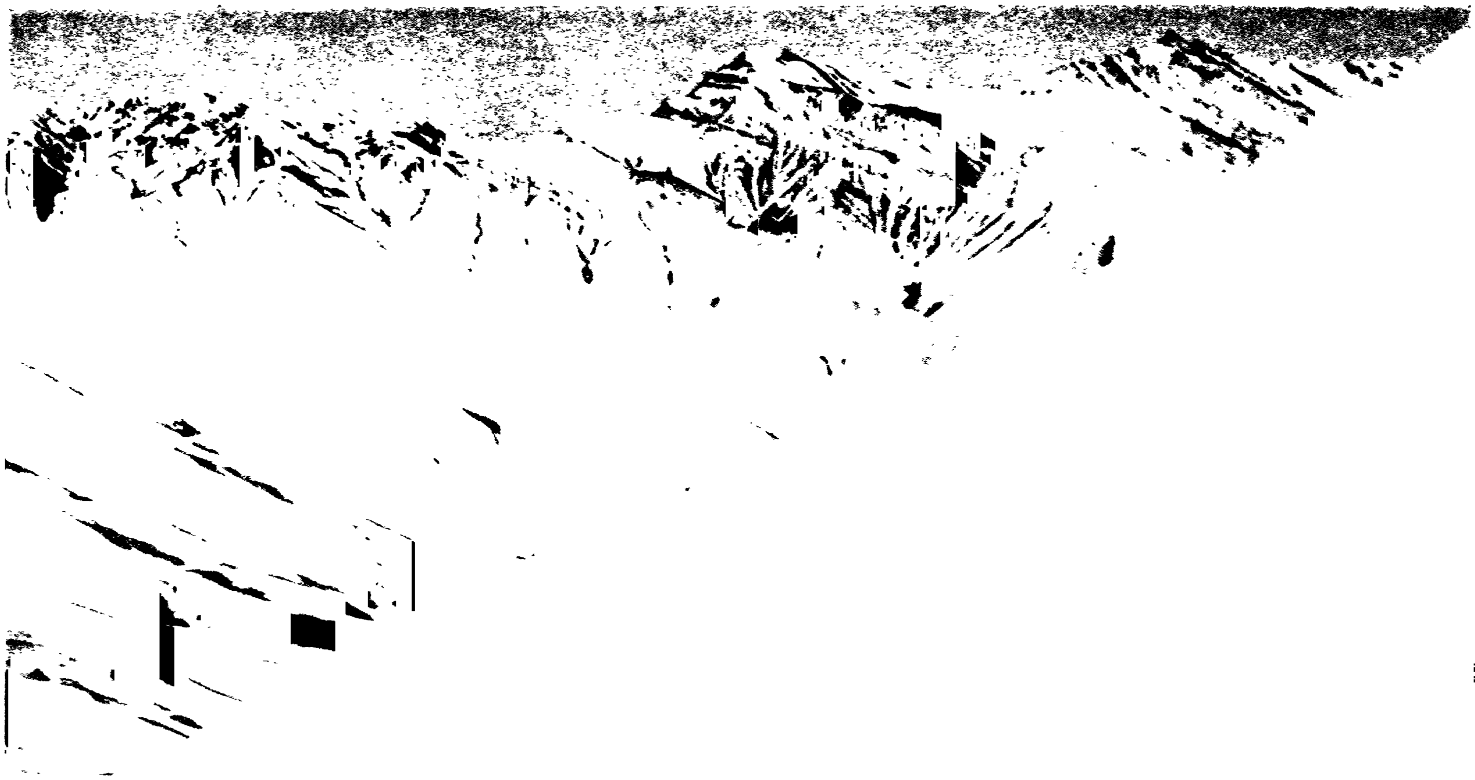
PHOTOGRAPH XI.



With the permission of D. G. S. I.] [*Photo by Dr. E. H. Pascoe.*

UNCONFORMITY BETWEEN HORIZONTAL PEGU AND IRRAWADDY BEDS. SADAING, MYAUK CHANG, BURMA.

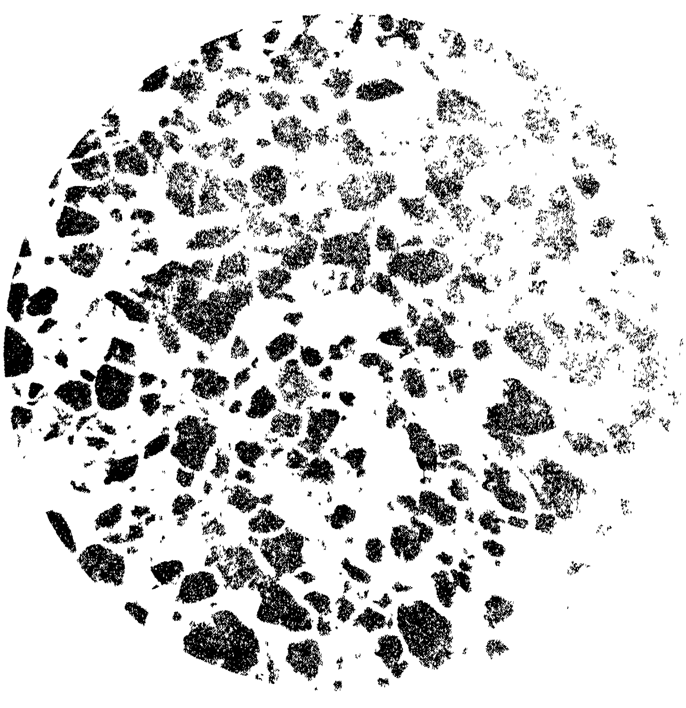
PHOTOGRAPH XII.



With the permission of D. G. S. I.] *[Photo by Sir H. H. Hayden*

UNCONFORMITY BETWEEN SILURIAN AND CARBONIFEROUS STRATA (NOTE DIFFERENCE OF DIPS OF BEDS IN FOREGROUND). MUTH, SPITI, HIMALAYA.

rocks, conglomerates, sandstones, etc., are nearly always rounded. Their shape may often be a guide to the mode of formation of particular beds. For example, river pebbles, because they are steadily rolled in one direction (down-stream), tend to assume the shape of prolate spheroids, the axis of the spheroid being horizontal and longer than the diameter of the circular section. Seashore pebbles, on the other hand, because they are pushed and pulled up and down the beach by the rising and receding tides, are flat; they assume the shape of oblate spheroids, the axis of the spheroid being vertical and shorter than the diameter



By favour of I. E. I.] [*C. S. F.*

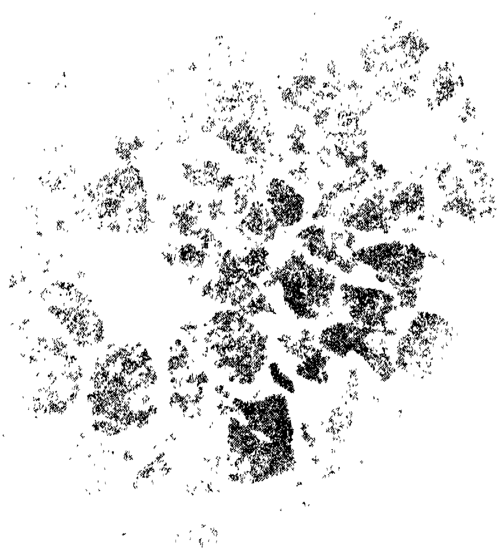
PHOTOMICROGRAPH 9.

Section of a ferruginous sandstone. Shows angular grains of quartz in a matrix of limonite. ($\times$ 25 dia.)

of the circular section. River sand is, as a rule, sharper than sea sand, owing to its being nearer its source of origin and consequently less worn and rounded.

Textures Affecting Porosity.—The rounded grains of sedimentary rocks touch each other without interlocking when the material becomes consolidated; a considerable portion of the rock is therefore empty unless filled, later, with a cementing matrix (see Photomicrographs Nos. 9 and 10, Reg. Nos. 1067 and 1068 respectively). The volume of this interstitial space as compared with the total volume of the rock varies greatly.

In clays and soft chalk, the pore-space volume may be as much as 50 per cent. of the whole volume of the material. In soft sandstones, it may vary from 20 to 30 per cent. In hard sandstones, the porosity may be only 15 per cent. Slates and shales have a porosity less than 6 per cent. Hard, massive limestones have a smaller amount of pore-space, sometimes less than 3 per cent. Fine-grained quartzites and most igneous rocks are practically impervious, their porosity not exceeding 1 per cent. The porous or impervious nature of a rock is dependent on the size of the pore-spaces. Clays—although with a large inter-



By favour of I. E. I.] [*C. S. F.*

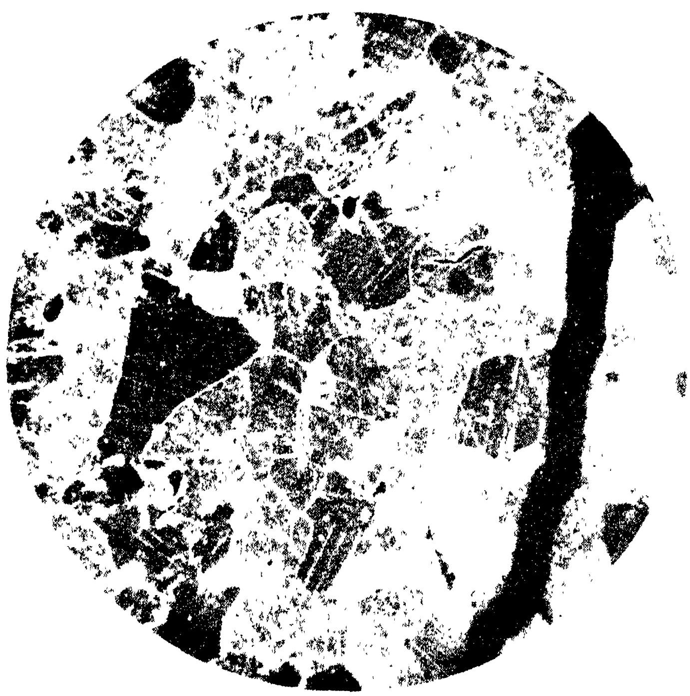
PHOTOMICROGRAPH 10.

Coarse sandstone with grains of quartz partly cemented in a matrix of secondary silica. Some of the pore spaces have not been filled up. (× 25 dia.)

stitial volume—are practically impervious because the pore-spaces are exceedingly small; the dry material is, however, capable of absorbing appreciable quantities of water. Chalk is porous because the pore-spaces are relatively large. Sandstones are porous for the same reason. Quartzites, on the other hand, are not only impervious, but they do not absorb water. The same is true for the massive limestones (see Photomicrograph No. 11, Reg. No. 1065). In these rocks it is the fissures and joints which hold large volumes of readily given up water.

Classification.—The commonest types of the sedimentary rocks are varieties of sandstones (arenaceous type), clays and shales (argillaceous type), and limestones (calcareous types). The relative abundance of these rocks in the crust of the earth has already been discussed. The chemical composition has also been indicated on a previous page.

Sandstones.—Several varieties of sandstones occur: some with a porous texture and others with an interstitial matrix of material such as carbonate of lime, ferric oxide, silica, etc. The aggregate usually consists of grains of quartz. The rock



By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 11.

Granular-textured crystalline limestone (marble) showing cleavage planes in the crystals of calcite. (× 25 dia.)

may be coarse- or fine-grained, friable (soft) or compact (hard). Their specific gravity varies from 2·65 to 3·00, and the weight per cubic foot of blocks may be 160 lb. for the porous types and 175 lb. for varieties with a ferruginous matrix. Porous sandstones are generally not as strong or as durable as the cemented types. Much, however, depends on the degree of consolidation of the porous varieties. The average crushing strength of hard, coarse-grained sandstone is about 600 tons per square foot, as against 400 tons per square foot for fine-grained types. They may occur in massive beds with few joints,

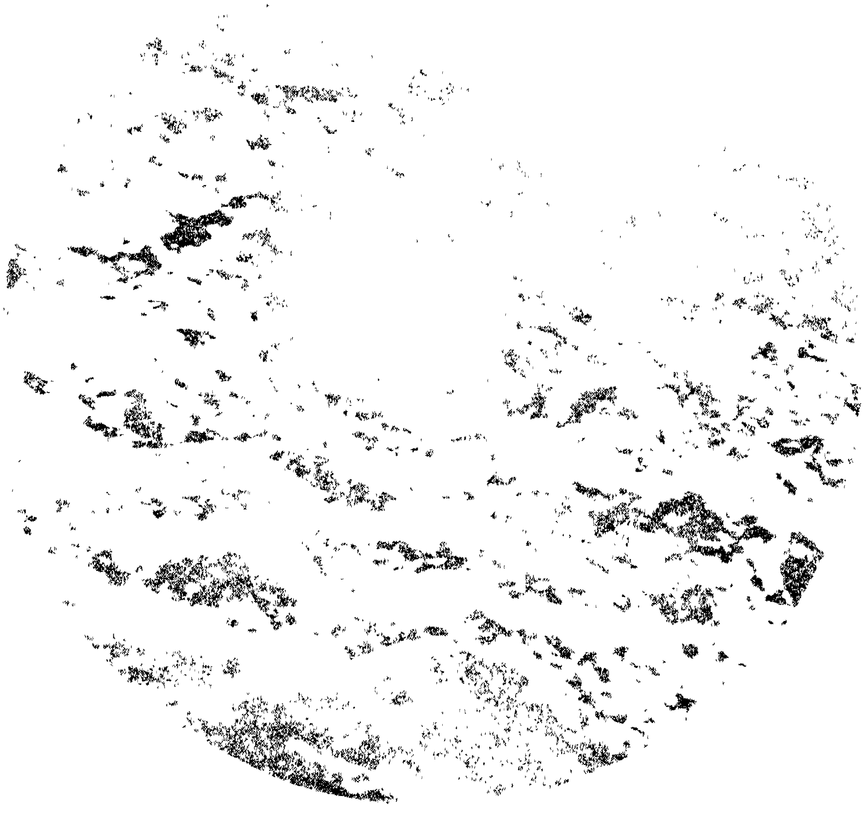
and may at times allow of the quarrying of enormous blocks. Thinner beds sometimes contain large slabs, which can be cut up into long stone pillars or into paving flags. Laminated sandstones are not rare, and frequently produce excellent flagstones particularly those varieties with appreciable quantities of felspar.

Shales and Clays.—These argillaceous rocks are nearly always fine-textured and often laminated. They, however, vary in composition: some types merge into the sandstones, while others are intimately related to the limestones. The soft clays differ greatly in composition (from ferruginous brick-clays to cream-coloured fire-clays). The more compact shales are the least useful, as they are generally too hard to pug for brick-making and too soft to use for building purposes. The hard slates, on the other hand, are most valuable, as they have one well-developed, closely-spaced cleavage. Some good roofing slates have a crushing strength equal to that of granite, i.e. 800 tons per square foot, and they stand a transverse load better than any other kind of rock. Softer, clay slates have a crushing strength of about 400 tons per square foot. The normal shales are much weaker. The specific gravity of shale is about 2·60, and a cubic foot weighs, roughly, 155 lb. Slate, on the other hand, has a specific gravity of 2·72, and a cubic foot weighs, approximately, 170 lb.

Limestones.—These rocks vary considerably in colour, structure and texture. They may be white, grey, pink, brown or black, and occur in great, massive beds or in thinly-laminated strata or in soft deposits of chalk. In many instances they consist largely of coral or other calcareous fossil-matter such as shells, crinoid, etc.; in other cases they are unfossiliferous. The texture may be amorphous, oolitic, granular, or compact and crystalline. All limestones are soluble in water, particularly water charged with acids. Calcium carbonate is the predominant constituent of limestones, although certain dolomitic varieties containing magnesium carbonate are common. These types are usually more insoluble than the pure, true limestones.

Limestones are of great importance to an industrial country; they are usable for building stone, lime, cement, making flux for ironworks, etc. Much depends on the physical strength and chemical purity of the stone in deciding its most advantageous disposal. The specific gravity of hard, massive limestone is about 2·70. A cubic foot of this type of rock weighs as much as 170 lb. whereas an equal volume of chalk weighs, roughly, 120 lb. The crushing strength of a good, hard limestone is, roughly, 400 tons per square foot. The hardest normal lime-

stone can be easily scratched with a steel knife, and all limestones effervesce when treated with an acid. Hard limestones are consequently very much softer than compact, massive sandstones. During recent years, certain peculiarities have been noticed in connection with the adhesiveness of various minerals and rocks to grease and tar. The modern practice of protecting the surface of roads with an asphaltic carpet has resulted in the



By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 12.

Augen gneiss, showing foliated arrangement of constituent minerals. (× 25 dia.)

use of greater and greater quantities of hard, massive limestones as road metal. The tar is drawn down into the crevices between the fragments and effectively reduces the grinding action which takes place between these fragments in the bed of the road when the road is subjected to heavy traffic. In such cases, the "metalling" should be laid dry, tarred, rolled and surfaced without the application of water.

THE METAMORPHIC ROCKS.

Literally, any altered rock is a metamorphic rock, and, strictly speaking, the sedimentary types previously described are of this class. However, for purposes of utility, the term metamorphic is used only for those representatives of the igneous and sedimentary rocks which have been subjected to great static pressure or exposed to intense dynamic force, or influenced by both, deep

By favour of I. E. I.] [*C. S. F.*

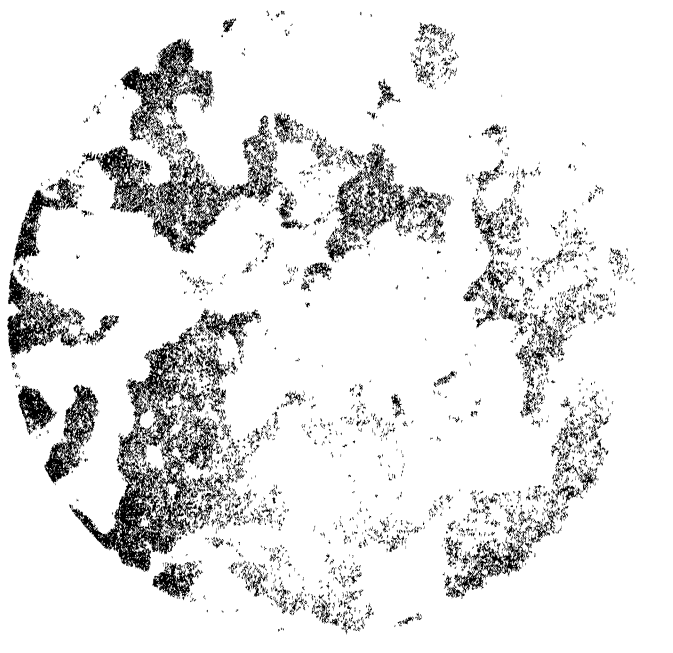
PHOTOMICROGRAPH 13.

Fine-grained schist, showing laminated structure. (× 25 dia.)

within the earth's crust, and have, as a result, undergone a noticeable change in structure, texture or mineral composition.

Ortho-gneisses and Schists.—Great static pressures seldom produce any change in the texture of igneous rocks, although in some cases new minerals may result by the paramorphic or metathetical redistribution of the components of the rock. Dynamic forces, on the other hand, induce a structural foliation, and result

in the formation of the so-called ortho-gneisses and ortho-schists, i.e. gneisses and schists which have been produced by the dynamic metamorphism of igneous rocks. This foliation or schistosity produces a banded or bedded type of rock which is often far superior to the normal igneous rock in resisting transverse strain. The foliation planes of weathered gneisses and schists, however, constitute channels for the percolation of water, so that it is advisable, when locating dam sites on such rocks, to have the length of the dam parallel to the direction of foliation. The gneisses and schists can generally be readily quarried and dressed



By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 14.

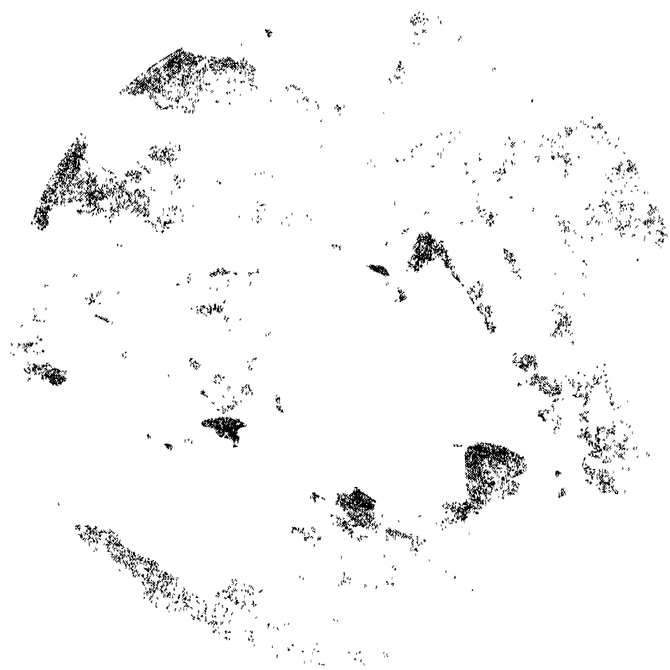
Typical texture of a granulite. This consists of diopside, green hornblende and calcite. (× 25 dia.)

for building purposes. Their crushing strength (on bed) is similar to the igneous rocks to which they are related. Some varieties have great resistance to transverse strain and can be used as stone beams. The specific gravity and weight per cubic foot are also similar to the igneous rock groups. Some granitoid types are coarse-textured, but the more severely sheared, schistose types have a fine-grained texture.

Photomicrograph No. 12 (Reg. No. 760) shows a thin section of a coarse "augen" gneiss as seen under the microscope. In many cases the same appearance, on an even larger scale than is shown in the photograph, is visible in hard specimens. Photo-

micrograph No. 13 (Reg. No. 762) represents the section of a schist with granula texture. Photomicrograph No. 14 (Reg. No. 838) gives an excellent idea of the granular texture of certain types of metamorphic rocks which have undergone re-crystallisation. Photomicrograph No. 15 (Reg. No. 1069) is a section of a biotite granite.

Paramorphic Types.—The sedimentary rocks—the sandstones, clays and shales, and the limestones when subjected to enormous static pressure or severe dynamic strain or combinations



By favour of I. E. I.] [*C. S. F.*

PHOTOMICROGRAPH 15.

Granite, showing granular texture with grains of quartz, felspar, brown mica (biotite) and a long needle of apatite. (× 25 dia.)

of these forces—undergo very important changes. Under great pressure the sandstones are converted into quartzites, the shales become clay-slates and slates, the limestones become crystalline (marble). In each of these cases, the metamorphic representative is generally more dense in texture, superior in strength, and far more durable than the original rock. When subjected to dynamometamorphism, foliation or banded structures are induced and certain characteristic minerals develop. The shales or slates are converted into phylites, mica-schists, staurolite-schists, and sometimes into gneisses (the coarser texture being due to induced

crystallisation). The limestones are transformed into calcareous (calc-) gneisses, pyroxene-gneisses, crystalline limestones, marbles, etc. Photomicrograph No. 14 (Reg. No. 834) shows the texture of a pyroxene granulite, while Photomicrograph No. 11 (Reg. No. 1065) is a section of a crystalline limestone. These gneisses and schists of sedimentary origin are frequently referred to as para-gneisses and para-schists, to distinguish them from the type related to the igneous rocks. There are endless varieties of such rocks. It is almost futile to endeavour to even summarise their characteristics in this book. Their strength and durability depend largely on their component minerals and the mode of aggregation, size and shape of the individual mineral grains. In general, the types with a granular texture are strong; those with an interlaced, fibrous texture are tough; while those with insoluble component minerals have good weathering properties. Occasionally some beautiful (ornamental) varieties occur, but as a rule they are local and possibly restricted to a single band.

Most gneisses and schists resist abrasion better when the foliation planes are perpendicular to the wearing surface. In building, it is best to have the foliation planes horizontal, so that the weight falls transverse to the foliation.

CHAPTER III

THE COMMON ROCK-FORMING MINERALS

PRIVATE, neatly-labelled collections of minerals are more frequently kept and examined than is often supposed. In some cases the petrological names have proved a difficulty, and more popular names such as greenstone, freestone, whinstone, etc., have been used. However, in this connection considerable assistance is available in the form of two useful books, *Elements of Mineralogy*, by F. Rutley, revised in 1918 by H. H. Reid, and *The Nomenclature of Petrology*, by Arthur Holmes. Collections of minerals and rocks become far more interesting if they are studied in a practical way, i.e. by determinations of specific gravity, hardness, cleavage, adhesiveness to grease, examination of thin sections under the microscope, etc. Unfortunately, the idea is prevalent that the cutting of thin slices of a rock or mineral is difficult, particularly when in camp. This is not true. It is possible to train an intelligent servant to cut sections in two or three months. The apparatus required is simple and inexpensive. However, this aspect of the study of specimens will be discussed later.

According to the geologist,

"Rocks are aggregations of simple mineral bodies or mineral matter. The minerals which compose the various forms of rocks may occur in crystals of sufficient dimensions to allow of their individual detection with the naked eye, or they may exist in forms so minute as to render their individualisation possible only with the high powers of the microscope . . . also before it is possible to intelligently study the rock masses of the earth's crust, it is first necessary to be acquainted with the minerals of which the rocks are composed. Minerals are aptly compared to an alphabet and the rocks to a series of words constructed therefrom." (*An Introduction to the Chemical and Physical Study of Indian Minerals*, by T. H. Holland.)

Definition of a Mineral.—"A mineral is a body produced by the processes of nature, having a definite chemical composition and, if formed under favourable conditions, a certain characteristic, molecular structure which is exhibited in its crystalline form and other physical properties." (*Text-Book of Mineralogy*, by E. S. Dana.)

There are over a thousand distinct minerals known to science, but of these only a relatively small number are in any sense

abundant, and very few form the essential constituents of rocks. The most important rock-forming minerals are: (1) orthoclase, plagioclase and other felspars; (2) quartz; (3) augite, hornblende, olivine and other ferro-magnesian minerals; (4) the micas, both black and white varieties; (5) magnetite, hematite and limonite; (6) the titanium minerals, rutile and ilmenite; (7) kaolin, etc.; (8) dolomite and calcite; (9) apatite, zircon, etc.; and (10) gypsum, carbon and other substances.

The Physical Characters of Minerals.—The chief physical characters of the various rock-forming minerals are their (*a*) shape and structure; (*b*) form of aggregation; (*c*) cleavage; (*d*) fracture; (*e*) hardness; (*f*) tenacity; (*g*) solubility; and (*h*) behaviour when subjected to rapid changes of temperature. These characteristics largely determine the physical properties of the rocks in which they predominate.

(*a*) *Structure.*—By far the greater part of the mineral components of a rock consist of imperfect crystalline grains. The prevailing shapes of these particles may be: (i) elongated or of *columnar form,* such as the prisms and needles (of amphibole), bladed and acicular types (kyanite), fibrous varieties, including those with silky, separable fibres (asbestos) or stellate forms (stibnite); (ii) rounded and *granular,* with irregular, interlocked grains (calcite in marble, see Photomicrograph No. 9); and (iii) flat, sheet-like or tabular (*lamellar* structure) shapes with platey, leaf-like varieties—some straight and others curved and bent. Mica has this lamellar structure highly developed. The term *micaceous* is often used when the bulk of a rock consists of thin flakes of a particular mineral (e.g. micaceous hematite).

(*b*) *Form of Aggregation.*—Much depends on the size and condition of the mineral components. They may be large—some crystals of beryl are over a yard long and more than 18 inches across—or they may be so small as to appear invisible to the naked eye. These remarks apply to the *crystalline* grains only. The same mineral may occur in a *crypto-crystalline* condition or it may even be *amorphous.* Quartz, chalcedony (agate) and opal are, respectively, three such forms of the substance known as silica (SiO_2). No trace of crystalline structure is visible in opal, even when it is examined under the microscope. This condition or form of a mineral substance may at times greatly influence the physical and chemical behaviour of a rock when exposed to certain atmospheric agents (weathering, etc.). It may result in the avoidance of an otherwise excellent ornamental building stone. The two substances, pyrite and marcasite, are identical in chemical composition, yet the latter oxidises far more readily in moist, warm air and produces ugly, brown patches on the stone.

(*c*) *Cleavage.*—In most crystalline bodies there is a tendency, when the mineral is strained, to split easily along certain definite directions and yield smooth plane surfaces. This property or cleavage is named according to the direction of the plane of separation. For example, (1) fluorspar (Blue John) has four well-developed cleavages parallel to the faces of an octahedron: it is said to have *octahedral* cleavage; (2) calcite has three easy cleavages parallel to the faces of a rhomb, and is therefore said to possess *rhombohedral* cleavage; (3) a mineral with three cleavages at right angles to each other would have *cubic* cleavage; (4) minerals with prismatic, acicular or fibrous structure (hornblende, kyanite, asbestos, etc.) have two well-developed cleavages parallel to the long axis of the mineral particles, consequently these minerals are said to possess *prismatic* cleavage; (5) mica has one perfect direction of cleavage. Exceedingly thin sheets or flakes can be split off parallel to the base of the flat, hexagonal-sectioned prisms in which mica crystals frequently occur. Mica, therefore, is said to have a perfect *basal* cleavage. The degree of cleavability of the material on opposite sides of a cleavage plane varies greatly. It may be difficult or simple to split different minerals along the same cleavage direction. Similarly, if a mineral possesses two cleavage directions, it is possible one may be more separable than the other. This cleavability is spoken of as

highly perfect (in mica, calcite, etc.),
perfect (in felspar, pyroxene, etc.),
distinct (in olivine and other minerals), and
imperfect or *difficult* (in corundum, analcite, etc.).

(*d*) *Fracture.*—The term fracture is used to define the kind of surface which is obtained on breaking a crystalline mineral in a direction other than that of the cleavage, if such exists. If the cleavage of a mineral is well developed, as in calcite, it is difficult to obtain a fracture surface. The mineral will break up in cleavage fragments. Quartz, garnet and several other minerals have practically no cleavage and consequently only break by fracture. An amorphous body (restricting ourselves to minerals) has no cleavage, and is only liable to fracture. The common types of fracture are: *conchoidal*, with curved, shell-like surfaces; *even*, when the surface, although rough, approximates to a plane; *uneven*, when the surface is rough and irregular; and *hackly*, when there are sharp, jagged elevations.

Cleavage planes are directions of weak cohesion in a mineral. A hard, brittle mineral like felspar, with two highly-developed cleavages, will readily break up, even under comparatively gentle impact, into angular fragments; whereas quartz, a mineral of

similar hardness but devoid of cleavage, will merely become rounded by such treatment.

(*e*) *Hardness.*—The hardness of a mineral is measured by its resistance to abrasion, and is usually determined by scratching a smooth surface of the mineral. If a mineral can, but with difficulty, be scratched with an ordinary steel knife and can itself scratch window glass, it will have an approximate hardness of 7 on the accompanying relative scale of hardness, where

Common foliated talc	= 1,
Gypsum or rock-salt	= 2,
Transparent calcite (Iceland spar)	= 3,
Crystallised fluorspar	= 4,
Cleaved orthoclase felspar	= 5,
Quartz (rock crystal)	= 6,
Topaz	= 8,
Fresh cleavable corundum	= 9 and
Diamond	= 10.

The hard minerals, those with a hardness exceeding 6, are most frequently oxides and silicates of aluminium. Among these the heavier minerals (with greater specific gravity) are usually harder than the others, the greater density evidently signifying a closer molecular packing of aggregation. In contrast to these aluminium silicates, the heavy metals, gold, lead, etc., are soft. They possess, however, certain properties, malleability, etc., which are absent in the minerals which have been discussed.

(*f*) *Tenacity.*—Hardness and tenacity are physical properties which appear to be determined by the elasticity and cohesion which exist between the molecules of a crystal. The tenacity or strength which holds the molecules together varies greatly and induces the following properties, for which certain minerals are noted. Minerals are said to be *brittle*, when they powder readily under attrition (calcite, felspar, etc.) ; *sectile*, when they can be cut as well as powdered (gypsum) ; *malleable*, when they can be cut and beaten flat (the metals alone have this property) ; *flexible*, when they can be bent but remain bent if not forcibly straightened (talc) ; *elastic*, when they are capable of recovering their shape if distorted within certain limits (mica).

(*g*) *Solubility.*—On a previous page it was shown that a mineral substance may be present in more than one condition—crystalline or amorphous. The solubility of the substance will generally be very different in each condition, e.g. quartz is practically insoluble in certain alkaline waters, while opal is distinctly soluble. There are greater differences in the solubility of different minerals in a common solvent, e.g. calcite (calcium

PHOTOGRAPH XIII.

With the permission of D. G. S. I.] *[Photo by Sir H. H. Hayden.*

SHOWS THE EFFECT OF THE SOLVENT ACTION OF WATER ON BEDS OF FOLDED CARBONIFEROUS LIMESTONE. LIPAK, KANAWAR, SPITI, HIMALAYA.

carbonate) is easily soluble under certain conditions, whereas magnesite (magnesium carbonate) is far less soluble when exposed to the same solvent. The question of solubility is often of considerable importance, as noted in the case of limestones in connection with reservoir sites and the location of dams. It has to be carefully investigated also in connection with the choice of rock for building purposes in a manufacturing region. Chemical works particularly, by the acid fumes emitted into the air, cause a serious disfiguration of the fine, carved facings of beautiful buildings. The Houses of Parliament, in Westminster, have had to be carefully examined and the exposed stone surface elaborately treated, in order to preserve the masonry against corrosion from the acid present in the London air.

The rapid oxidation of marcasite (iron sulphide) has already been referred to. This mineral on being oxidised produces ugly, brown patches on the surface of the exposed stone. In choosing ornamental stones the presence of and subsequent alteration of such minerals should be carefully borne in mind. Gypsum and a few other comparatively rare minerals also undergo rapid decomposition on exposure, and their presence should be sufficient reason for avoiding the use of the material in which they occur. In some of the new buildings of Imperial Delhi, an efflorescence, traceable to the brickwork backing, has made its appearance on the exposed stone surface of the shady walls.

(*h*) *Temperature Changes.*—The peeling off which is sometimes noticeable on some stone buildings, which are exposed to the fierce heat of the sun in the day followed by sharp frosts at night, is generally due to the strain produced by the unequal expansion of the component minerals in the rock. The cubical expansion of a number of the more important rock-forming minerals have been determined (see Merrill, *Stones for Building and Decoration*, 1903, p. 434).

The following co-efficients of cubical expansion are of interest :—

Quartz	0·000036
Orthoclase felspar	0·000017
Adularia felspar	0·000018
Hornblende	0·0000284
Tourmaline	0·000022
Garnet	0·000025
Beryl	0·000001
Calcite	0·00002
Dolomite	0·000035

The co-efficients of thermal expansion of plagioclase, augite, diopside, and olivine are not available ; they probably have the

Class.	Rock-forming Minerals.	Compositi	ks.
I. NATIVE ELEMENTS—			
(a) Non-metals			
(b) Semi-metals			
(c) Metals			
II. SULPHIDES, SELENIDES, Etc.			
(a) Of semi-metals			
(b) Of metals	Pyrite	Sulphide of Ir	sedimentary rocks.
	Marcasite	Sulphide of Ir	tions which cause
III. SULPHO-SALTS—			
(a) Sulpharsenites, etc.			
(b) Sulpharsenates, etc.			
IV. HALOIDS—			
(a) Anhydrous			
(b) Oxychlorides			
(c) Hydrous			
V. OXIDES—			
(a) Anhydrous			
1. Non-metals	Quartz	Pure Silica	. Sandstones are nposed of quartz
	[illegible]	[illegible] Magnesia, Ir Aluminia	
	Serpentine	Hydrous Magn Silicate	ct of ultra-basic
	Talc	Hydrous Meta of Magnesiu	ct of ultra-basic
	Kaolinite	Hydrous Silic Aluminium	c rocks usually
3. Columbates			
4. Phosphates, Etc.—			
(a) Anhydrous	Apatite	Phosphate and ide of Calc Phosphate an ide of Calciu	ch in this mineral.
(b) Hydrous			
5. Sulphates—			
(a) Anhydrous			
(b) Hydrous	Gypsum	Hydrated Calci phate	ation product in commonly found salt lakes.
6. Tungstates			
VII. SALT OF ORGANIC ORIGIN			
VIII. HYDRO-CARBON COMPOUNDS			

following approximate values: i.e. 0·000022, 0·000030, 0·000032 and 0·000036 respectively.

The relative values of the co-efficients of cubical expansion of the various minerals are important. A rock-like granite, consisting largely of quartz and orthoclase, must be subject to considerable strain when exposed to great heat and then suddenly cooled. Similarly, a dolomitic marble, composed of equal proportions of calcite and dolomite, or a dolerite with plagioclase felspar and augite, will certainly fracture if heated and then suddenly chilled. A diorite or epidiorite, with hornblende and plagioclase felspar, would be more resistant; and a sandstone (quartzite) of compact texture might have considerable linear expansion.

Classification of Minerals.—In the accompanying table, showing the physical characters of the common rock-forming minerals, the classification laid down by Dana has been adopted. Eight classes are instituted, and each has been subdivided for convenience of study. Except for quartz, in Class V under Oxides, it is seen that most of the rock-forming minerals belong to Class VI, Oxygen Salts, and chiefly to the group designated as Silicates. Detailed information on the crystal forms, optical properties, etc., of these minerals will be found in most text-books on mineralogy.

CHAPTER IV

THE PHYSICAL PROPERTIES OF ROCKS

THE most important physical properties of rocks which are required for engineering purposes are their durability, hardness, toughness, porosity and strength. These properties are dependent on the mode of occurrence, type and condition of the rocks, and are modified by their subsequent treatment when exposed to the solvent action of acid or salt waters, great changes of temperature and, when subjected to mechanical pressure, abrasion or impact.

Durability.—Rocks, as previously stated, are

"for the most part composed of minerals, and minerals for the most part are definite chemical combinations which are only, as a rule, permanent under stable conditions. If the minerals are submitted to new conditions, quite different from those under which they were formed, with new chemical and physical factors operating on them, they will tend to change into other minerals, that is, to turn into new chemical combinations, which will be most stable under the new conditions." (See *Rocks and Rock Minerals*, by L. Pirson, p. 333.)

Those igneous rocks, whose constituents have rapidly crystallised and cooled from a highly-heated, liquid condition, are particularly liable to undergo paramorphism or decomposition. Numerous cases are known in which dolerites have gradually changed to epidiorites as a result of the augite being converted into green hornblende. The peridotites are well known for their alteration to serpentine, and even into clay-like masses, owing to the instability of the mineral olivine.

The sedimentary rocks seldom suffer a metathetical redistribution of their constituents. Sandstones and shales, under considerable pressure, become compact quartzites and slates respectively. They suffer no chemical or mineral change, and are therefore relatively durable rocks. Marble is a more compact, stable form of limestone, but, owing to its comparative softness and solubility, it is liable to weather badly under certain conditions.

The most stable minerals in the upper zones of the earth's crust appear to be quartz, hornblende (amphibole), albite (felspar),

and biotite (mica); consequently, on theoretical grounds, some granites, hornblende syenites, diorites, epidiorites and similar rocks, including certain metamorphic rocks and the sedimentary varieties already mentioned, should be the most durable types. They are durable from the point of view of mineral stability when exposed to normal weathering influences.

Hardness.—This physical property depends, partly, on the hardness of the component minerals of the rock and the cohesion between the several particles which compose the rock. Fine-grained granites, owing to the presence of quartz grains, are usually harder than any other type of igneous rock, although they are not as hard as quartzites with a cementing matrix of secondary silica. Sandstones, without any cementing matrix, are friable rather than soft, because the loosely held grains of quartz are rubbed off the surface of the stone. Pure marbles are relatively softer than dolomitic marbles, because calcite is softer than the magnesian carbonate, magnesite.

Toughness.—Toughness is best described as resistance to impact. This property depends on the interlocked condition of the mineral constituents and on the individual tenacity of the minerals. Interwoven needles and plates of hard, slightly elastic minerals will form an exceedingly tough rock (see Photomicrograph No. 8, Reg. No. 831). This interpenetrating structure of epidiorites, diorites and dolerites makes them particularly suitable for road metal and paving setts. An interlocked, granular texture (see Photomicrograph No. 14, Reg. No. 838) is also capable of producing a tough rock, if the individual grains are irregular, as in many granites, and not rounded as in most quartzites. Sandstones are not tough, because the grains are not only rounded but generally uncemented. The easy cleavability of calcite prevents marbles which have an interlocked, granular texture from being tough (see Photomicrograph No. 11, Reg. No. 1065).

Porosity.—It is best to estimate the porosity of a rock by the difference in weight of a specimen which has been soaked in water for 24 hours, under a hydrostatic head of 30 or 40 lb., and then dried for the same time at 105° C. The ratio of the volume of the water given off in drying to the total volume of the rock represents the porosity.

Rocks which have an interlocked texture, such as the igneous rocks, marble, most quartzites, and nearly all the gneisses and schists, have practically no porosity and are consequently impervious. The sedimentary rocks, e.g. sandstones, clays and limestones, contain a large volume of pore-spaces—in some cases as much as 20 to 30 per cent. of the total volume of the rock.

The pore-spaces in sandstones and chalk are relatively large and do not offer considerable resistance to the movement of water through them. Such rocks are said to be porous. On the other hand, the interstices in clays and soft shales are exceedingly small and offer great resistance to percolating water; consequently these rocks, although possessing considerable porosity, are impervious.

Strength.—The word strength as applied to a rock is not always used in the same sense. It usually refers to the ability of the rock to withstand crushing under direct pressure, as in blocks and columns, and is sometimes the resistance to fracture by transverse loads on stone beams. Many factors govern the strength of a given rock—the behaviour of the mineral constituents when exposed to atmospheric agencies, acids and salt-water, frost, heat, moisture, etc. In the following table the average crushing strength of various kinds of undecomposed rock, etc., are given :—

Crushing Strength of Building Stones.[1]

	Average tons per sq. ft.
Coarse, porphyritic granites	700
Medium-grained granites	1,000
Fine-grained granites	800
Doleritic basalts	1,000
Epidiorites and diorites	1,500
Sandstones, coarse, hard	600
Sandstones, medium to fine, hard	400
Marble, coarse to medium	800
Marble, fine to medium	300
Limestones, hard	400
Limestones, soft or oolitic	100
Slate, fine, hard	800
Clay-slate, hard	600
Clay-slate, normal	400
Brick, good	170
Cement	100
Concrete, 6 to 10 months old	75
Cement mortar	65
Brickwork, in good cement	50
Lime mortar	40
Brickwork, ordinary	25

N.B.—The pressure applied perpendicular to the plane of foliation, bedding or lamination. Stones generally begin to crack or split under about half their crushing loads. In practice, neither stone nor brickwork should be trusted with more than 1/6 to 1/10 the crushing load, according to circumstances.

The strength of stone beams can be roughly estimated from the details given in the Table on the following page.

[1] Fresh undecomposed specimens only.

STONE BEAMS (GOOD BUILDING GRANITE).

Depth in inches.	Clear Spans in Feet. 1	2	3	4	5	6	7	8	10	12	15	20
	Safe Centre Loads in Pounds.											
1	10	5	—	—	—	—	—	—	—	—	—	—
2	40	20	13	10	—	—	—	—	—	—	—	—
3	90	45	29	21	17	—	—	—	—	—	—	—
4	160	79	52	39	31	26	21	—	—	—	—	—
5	250	124	82	61	48	40	34	—	—	—	—	—
6	360	179	119	89	70	58	48	42	32	—	—	—
7	490	244	162	120	96	79	67	58	45	36	27	16
8	639	319	212	158	126	104	88	76	59	47	36	22
10	999	499	231	248	197	163	139	120	94	76	58	38
12	1,439	718	478	357	284	236	201	174	137	111	85	53
14	1,959	978	650	487	388	322	274	238	188	153	118	81
16	2,559	1,278	850	636	507	421	359	312	246	201	157	109
18	3,239	1,618	1,077	806	643	534	455	396	313	257	200	141
20	3,999	1,998	1,329	995	794	660	563	490	388	319	249	176
22	4,839	2,417	1,609	1,205	961	800	682	594	470	387	303	216
24	5,758	2,877	1,916	1,434	1,145	951	813	708	562	463	362	260
27	7,288	3,642	2,425	1,815	1,450	1,205	1,010	898	713	588	462	332
30	8,998	4,496	2,995	2,243	1,791	1,489	1,273	1,110	882	728	573	415
33	10,888	5,441	3,624	2,714	2,168	1,803	1,542	1,345	1,069	883	696	505
36	12,958	6,776	4,314	3,231	2,581	2,147	1,936	1,603	1,275	1,054	832	606

N.B.—If uniformly distributed over the clear span, the safe extraneous loads will be twice as great as those in the table.
For good slate on bed the safe loads may be taken at about 3 times;
For good sandstone on bed at about ½; and
For good marble or limestone on bed at about the same as those in the table.

FACTOR OF SAFETY TAKEN—1/10 BREAKING LOAD.

Trautwine's Pocket Book, 1907, p. 924.

From the above tables, it would appear that the igneous rocks, with their interlocked mineral components and absence of interstitial space, are, in general, stronger than the sedimentary types; while the metamorphic rocks, the gneisses and schists, quartzites, slates and marbles, etc., occupy an intermediate position in the scale of strength. It is, however, well known that many foliated rocks are superior in transverse strength to most igneous rocks.

In all types of rocks the medium-textured varieties are strongest. The weaker minerals in coarse-textured rocks usually crush, and by so doing involve the strength of the whole rock. The fine-textured varieties, on the other hand, appear to possess less cohesion between the particles.

Effect of Moisture on Strength.—As a result of tests carried out in the United States in 1890 (at Watertown Arsenal), it was found that, after alternate drying and soaking (at 100° C.), the crushing strength of the wet rock was usually considerably less than that of the dry rock. For example, the strength of

Granite became	0·837	of its original value;
Sandstone became	0·669	of its original value;
Limestone became	0·588	of its original value;
Marble became	0·462	of its original value.

Later investigations of the Physical Properties of Building Stones, by Messrs. Baldwin-Wiseman and Griffith (see Paper No. 3856, *Min. Proc. Inst. Civil Engineers*, vol. clxxix, 1907, p. 290, etc.), have shown that porous rocks are less affected than impervious rocks of the same porosity. It was thought that this was due to the water being more easily expelled from the larger pore-spaces of the porous rock. Interesting data, taken from the above-mentioned paper, are shown on the following page.

The Influence of Heat.—The co-efficients of thermal expansion (linear) of the various rocks discussed in the above table are also included in that table. Other determinations of the linear co-efficient of thermal expansion are available. One of these (see Adie, in *Trans. Roy. Soc. Edin.*, vol. xiii, p. 366) is particularly interesting, because it shows how the presence of moisture in a rock may seriously increase the co-efficient of thermal expansion. Much, of course, depends on the porosity, mineral composition, coarseness of texture, etc., of the rock. The following examples of well-known rock made this clear. The co-efficients of red Peterhead granite when dry = 0·00000498 per 1° F., when moist = 0·00000532 per 1° F. Corrennie granite (red variety), when dry, has a constant = 0·0000057, and in

Rock.	Porosity.	Crushing Strength in lb. per square inch.		Co-efficient of Thermal Expansion per 1° C.	Stress Produced by 1° C. Rise in Temperature in lb. per square inch.	Specific Heat Calories per gram.
		Dry.	Wet.			
Fine-grained, yellow sandstone (Millstone Grit)	per cent. 12	8,480	8,280	0·0000123	0·210	0·193
Fine-grained, red sandstone (Permian) ..	15	2,520	2,510	0·0000099	0·473	0·178
Soft Keuper sandstone	16·6	900	400	?	—	—
Hard Keuper sandstone	17·7	2,020	1,750	0·0000135	0·121	0·189
Compact quartzite	2·9	3,680	3,660	0·0000162	0·196	0·225
Compact limestone (freestone)	20	1,570	600	0·0000035	0·204	0·196
Bath (oolitic) limestone	17·8	1,140	770	0·0000048	0·141	0·170
White Carrara marble	0·78	4,450	4,400	0·0000087	0·857	0·204
Red rouge royal marble	0·93	6,420	4,500	0·0000058	0·670	0·200
Black Dinant marble	0·73	6,710	6,700	0·0000049	0·147	0·199
Red Peterhead granite	0·28	5,480	5,200	0·0000102	0·513	0·185
Grey Aberdeen granite	0·12	5,950	5,940	?	—	0·166
Green Diabase (dolerite)	0·24	6,070	6,030	0·0000097	0·731	0·181

grey Aberdeen granite, when dry, 0·00000438. Similarly, the co-efficients of (linear) thermal expansion of sandstones vary greatly from 0·00000953 in quartzitic types to 0·0000051 in soft sandstones. Slates have an average co-efficient of thermal expansion equal to 0·00000576 when dry. The co-efficient value may, however, vary from over 0·0000063 to less than 0·0000044 in certain classes of slate. The constants for various kinds of marble are nearly as variable as in sandstones—in some Sicilian (white) varieties the value is 0·0000078 when the stone is moist and 0·00000613 when dry. For Carrara marble the following values have been determined: 0·00000662 when moist and 0·00000363 when dry. The co-efficient of thermal expansion of black Dinant marble is stated to be as low as 0·000002 per degree when dry. The average value of the co-efficient of thermal expansion for dolerite, diorite and "trap" rocks, in general, is estimated to be, roughly, 0·00000449 per 1° F. (In comparing the values given above with those in the preceding table, it is to be remembered that the figures given in the table are per 1° C., whereas these are per 1° F.)

In the chapter on rock-forming minerals, attention was drawn to the possibility of internal strain being developed in certain rocks subjected to great variations of temperature.

An excellent example of the poor fire-resisting properties of a rock containing minerals of widely different co-efficients of thermal expansion is to be seen in London in the granite masonry at the base of Nelson's Monument in Trafalgar Square. On Armistice night (November 11, 1918) huge bonfires were lit by the rejoicing crowds in various parts of the square. Fortunately, the authorities intervened in time; but the effects of two of these fires can be seen in the disfigurement they caused. In the accompanying Photograph (XIV) the steps at the base of the column facing Cockspur Street are seen to be damaged, and the scaling of the plinth wall between the lions on the Whitehall side is plainly visible.

Thermal Conductivity.—Messrs. Baldwin-Wiseman and Griffith found that the thermal conductivity of various rocks was, roughly, as follows:—

	C.G.S. Units.
Sandstone	0·0062
Limestone	0·0055
Granite	0·0050

These differences are of greater interest to the physicist than to the engineer, because it is doubtful if the coolness of a house, even in a hot, sunny country, would be affected as much by the

PHOTOGRAPH XIV.

By favour of I. E. I.]

NELSON'S MONUMENT, SHOWING THE EFFECTS OF FIRE ON THE GRANITE AT THE BASE.

choice of building stone as it would by the thickness of the walls, etc.

Electrical Conductivity.—The electrical conductivity of various mineral substances is of particular value in some branches of engineering. The choice of marble or slate for switchboard panels necessitates an investigation of the electrical resistance of these stones. When perfectly dry, all rocks, from hard granites to the finest sand, have exceedingly high ohmic resistance (upwards of 100,000 ohms per cubic foot). The resistance falls when the material becomes wet; consequently, materials of a high degree of porosity, i.e. the sedimentary rocks, are in general not suitable for the purpose of making electrical switchboard panels. The igneous rocks and several metamorphic rocks—marbles, slates and sandstones—are suitable, if free from cracks or veins of metallic minerals. Marbles and slates are usually chosen because of their uniformity of colour and easy manufacture into slabs.

ELECTRICAL RESISTANCE.

	Resistance in ohms per foot cube of Wet Stone.
Millstone grit	660
Permian sandstone	580
Hard Keuper sandstone	1,160
Quartzite	14,300
Limestone	1,430
Bath oolite	930
Carrara marble	8,450
Rouge royal marble	11,500
Black Dinant marble	4,790
Peterhead granite	12,100
Diabase	54,600

There is another aspect of the electrical conductivity of various rocks which affects the choice of sites for the erection of radio-telegraph stations. It is known that the nature of the surface of the earth between two stations considerably influences the strength of the signals. A conducting surface (salt-water, i.e. the sea) allows the electro-magnetic waves to pass easily and without absorption. A non-conducting surface (hot, dry sand—a desert) allows the waves to enter the rocky material and are, to some extent, absorbed by the surface. Professor J. A. Fleming gives the following conductivities of various kinds of material and indicates the importance of water as a conducting medium (see *Nature*, lxxxii, 1909, p. 141).

ELECTRICAL RESISTANCE.

	Specific resistance in ohms per metre cube.
Mercury	0·000001
Sea-water	1
Fresh water	100 to 1,000
Moist earth	10 to 1,000*
Dry earth	10,000 upwards*
Wet sand	1 to 1,000*
Dry river sand	Very large*
Wet clay	10 to 100*
Dry clay	10,000 upwards*
Slate	10,000 to 100,000*
Marble	5,000,000*

* These materials owe their conductivity to interstitial water.

CHAPTER V

CHOICE OF MATERIALS

ACTUAL tests for ascertaining the approximate crushing strength, resistance to abrasion, toughness under impact, weathering qualities, etc., are naturally the most satisfactory means of ascertaining the properties of a rock. The engineer may not, however, be able to carry out these tests owing to the costliness of some of the apparatus required. In such cases a petrological examination can not only be carried out quickly, but will prove reliable. The best procedure is that of preparing thin sections of the rock and examining the slides under the microscope. Three or four such sections can be cut and mounted as slides in a day by a trained section cutter, so that in this way several samples can be collected in various parts of a quarry, sectioned and examined, and a very tolerable idea obtained of the material in the quarry. With a little practice it is possible to tell at a glance if any of the mineral components of a fresh-looking rock are decomposed. The altered condition of a single constituent, e.g. felspar on a medium-grained granite, may very seriously affect the strength and durability of the rock as a whole. Concrete in which the aggregate is granite with decomposed felspar, which has been used dry, will be subject to serious contraction. It is thought that the decomposition of the felspar continues, and that the kaolin, hydrous silicate of alumina, which is formed, extracts the necessary moisture from the matrix of the concrete, thereby producing shrinkage in the mass. A dam made of concrete with such ingredients is certain to contain cracks which might result in serious loss by leakage, or possibly in the collapse of the dam. Much obviously depends on the knowledge of the investigator. He should be able to identify the common minerals and rocks in hand specimens, and be familiar with the weathered appearance of the more important types of rock and their field relationships. If, in addition to this, he has trained himself to cut and prepare and examine either thin sections or polished surfaces of rock under the microscope, he will be equipped for very detailed work. The apparatus required for cutting and making microscope sections or for polishing rock surfaces is

simple and inexpensive. The whole outfit can be packed away in a box 18 inches × 12 inches × 10 inches, and it is possible to teach an intelligent Indian orderly to cut sections in three or four months. Numerous books have been published on the subject of microscopic examination of thin sections of rock and the determination of translucent and opaque minerals in transmitted and in reflected light.

The first glance at a section of a rock through a microscope reveals the size and shape of the component minerals, the open or interlocked aggregation of the grains, and the general texture of the rock. With a little patience it is possible to ascertain the several constituent minerals and their degree of alteration. All these little facts, when pieced together, provide sufficient data to enable an accurate opinion to be formed as to the suitability of the rock for various purposes. This aspect of the subject was briefly touched upon when discussing the more important types of rock in the chapter on the principal rock groups.

Clays.—There are numerous classes of clay, from the dark blue brick-clays and red, loamy varieties to the pale cream fire-clays and white, somewhat non-plastic, greasy kinds known as kaolin. The colouring matter in clay is usually an oxide of iron. When this substance is present in appreciable quantities the clay is generally readily fusible, and bricks made of this class of clay are liable to over-burning, with the formation of clinker bricks. This burnt brick is sometimes useful as a protective material for banks, etc., liable to the scouring action of streams. The colour of the bluish clays when burnt is generally dark or bright brick-red. If lime is present, the burnt brick is generally yellow or buff in colour. Purer clays stand much higher temperatures and merge into fire-clays, etc. The characteristic property of clay is its plasticity. It is a property which, being due to the physical rather than the chemical condition of the material, can only be determined by experiment. Some clays shrink enormously on drying or burning, and require an addition of sand or chaff, etc., to reduce this contraction. The subject of clay for various purposes is a very large one, the treatment of which is outside the scope of this book.

In many parts of the world the soil is impregnated with mineral matter (salts), which appears on the surface of the ground in dry weather as an efflorescence. If bricks are made of the clay of these areas, the salt, if not removed, will often remain unchanged in burnt bricks; consequently, when the bricks are used for building purposes, an encrustation of salt may in time appear on the exposed surfaces of the brickwork, particularly

on damp or the shady side of walls. The salts which most frequently cause these discolorations are the sulphates, chlorides, and carbonates of potassium, sodium, aluminium, magnesium, and especially calcium. An efficient method of detecting the presence of soluble salts in a brick is that known as Dr. Meckler's test. In this the brick (only unglazed bricks can be examined by this means) is placed over a fairly wide-mouthed bottle containing distilled water. Keeping the brick carefully pressed on the bottle, the combination is quickly turned over without allowing the water to spill, and the brick with the inverted bottle uppermost is supported on two glass rods over a dish. The brick will slowly absorb the water, which in turn will percolate through the brick to the lower surface, carrying any soluble matter with it. This water will be finally evaporated and leave behind an encrustation of salt, if there is any, on the under surface of the brick.

Sands.—The size of the grains determines whether a loose, gritty substance should be called a gravel, a sand, or silt. When the particles are all less than 0·01 mm. in diameter the substance is mud or clay. In fine silt, the particles vary in size from 0·01 mm. diameter to less than 0·05 mm. diameter. Coarse silt from 0·05 mm. to 0·1 mm. diameter. Fine sand is composed of grains from 0·1 to 0·25 mm. diameter; medium sand, 0·25 to 0·5 mm. diameter; coarse sand from 0·5 to 1 mm. diameter; and very coarse sand between 1 and 2 mm. diameter. The particles of gravel exceed 2 mm. diameter. (See *British Glass Sands,* by Professor P. G. H. Boswell.) Although there are many kinds of sands, composed of widely different substances, i.e. magnetite, garnet, zircon, monázite, etc., the term sand alone usually implies the presence of quartz grains only. In a number of cases sands are largely composed of equal-sized (graded) particles, either large or small. Sands composed of grains of assorted sizes are most common, and frequently require screening to obtain equal-sized grains for particular purposes, i.e. moulding sand. When used for making mortar, the angularity of the grains is an important factor. Quartz sand will usually be found in streams which drain large areas in which granite or sandstone rocks are exposed. River sand is as a rule more angular, i.e. sharper, than sea sand, because it is usually nearer its source of origin and is consequently less worn and rounded; but this is not a reliable guide, as river sands may be derived from sandstones which may represent the deposited sands of pre-existing rivers. The most efficient method of determination is that of taking samples of the sand and examining the grains with a lens or under the microscope. The precaution of washing sands which contain soluble salt is

not always taken, with the result that the mortar which is subsequently made may give rise to dampness and discoloration of interior walls.

Pebbles.—Pebbles may consist of a variety of hard rocks of igneous, sedimentary or metamorphic origin. The hardest and best-known pebbles are of quartzite. These pebbles, because of their great hardness, are very suitable for the aggregate of concrete. The whole object in the preparation of concrete is to reconstruct in the artificial stone a texture and mineral composition similar to those rocks which have the greatest strength, durability and toughness. The rounded, smooth surfaces of pebbles do not allow the cementing matrix to hold firmly, and it is therefore advisable to use broken pebbles, because the angular fragments bind much more strongly. Well-washed fragments of many fine- to medium-textured rocks, such as basalt, andesite and trachyte, are also very suitable for concrete making.

In the chapter on rocks (sedimentary rocks) reference was made to the shapes of pebbles of certain origin. River pebbles were said to be of an elongated shape (prolate spheroids) because they rolled steadily down-stream, while sea-shore varieties were said to occur sometimes as flat pebbles (oblate spheroids) because they were subjected to a sliding movement up and down the beach. The flatness may be due to the lamination of the original material and the elongation to the jointing of the rock from which the fragment has been derived. In the majority of cases, the pebbles are rounded and irregular in shape.

Road Metal.—It is well known that materials for road metal should have good wearing qualities and, consequently, be both hard and tough. The best rocks for road metal are those consisting of equal-sized grains of medium to fine texture, with an interlocked, ophitic arrangement of tough minerals of the requisite hardness—particularly basalt, andesite, trachyte, diorite and similar varieties. Hard, brittle stones like quartzites or the relatively friable sandstones are unsuitable, as the fragments are crushed against each other under heavy traffic, with the result that they grind to dust. The hardest argillaceous rocks, such as phyllite and slate, are too soft to withstand the heavy wear of a road surface. Hard limestones, although relatively soft and friable on ordinary watered roads, are being used to a considerable extent in a particular way. The fragments are laid dry and tarred, and after preliminary rolling a protective carpet of asphalt and sand is put on as the wearing surface. The advantages of using material which has been hand-broken in preference to that which has been obtained from a jaw-crusher have frequently been discussed. The blunt-pointed hammer

breaks the stone, by impact, along definite directions without damage to the body of the stone, whereas the machine crushes the whole stone, loosens its texture, and makes it less tough and more friable.

There are several considerations which affect the choice of road metal. If water is to be used in the construction of a road, perhaps well-washed fragments of the basic types of the igneous rocks are the most suitable; this material wears exceedingly well, and the decomposition products of the mineral components result in the formation of secondary minerals between the fragments, which cement adjacent pieces and prevent them rubbing against each other, thereby assisting in the consolidation of the road. When tar is to be used, the road metal should be used in a perfectly dry condition, as the tar holds better to a dry surface than to one which is wet. Experimental work has shown that limestone and tar adhere to each other particularly well, whereas tar and quartzite do not; the igneous rocks occupy an intermediate position with regard to this peculiar property of adhering to tar. Limestone, however good, is not hard enough to resist abrasion when exposed to steel-studded tyres and iron shoes of horses, consequently such road surfaces require protection. The method of saving such roads is to cover the surface of the road metal with a thin layer of asphalt in which coarse sand has been mixed, and also to sprinkle sand on the asphalt "carpet" while it is still hot; by doing this, the actual wear is taken by the grains of hard quartz. This type of protective carpet is also being used for other kinds of road surfaces.

One of the most serious difficulties in road making appears to be the grinding action which takes place between adjacent fragments of the road metal when the road is used by heavy vans, etc. Tar, by sinking into the crevices of the road metal, appears to be an excellent remedy for this kind of road deterioration, as it acts as an elastic cushion between the fragments.

Another evil is that of the development of ridges, from 16 to 24 inches apart, across the length of a road. All classes of roads, except those paved with stone setts, appear to become corrugated when used by heavy, fast-moving vehicles. Various explanations and remedies have been suggested. To a geologist, this phenomenon has all the aspects of an expansion, longitudinally, of the whole volume of the road-metal bed, combined with "creep" due to the tangential pull and push effect, which is exerted on the road surface by the wheels of fast-travelling, heavy vehicles. The thicker and more uniform the nature of the road metal, the further apart will be the corrugations, while thin surface dressings will wrinkle more closely. It resembles, in miniature, certain pheno-

mena seen on a vast scale in some parts of the world. For example, the earth movements in Asia have wrinkled up the bedded strata of a marine region into the highest mountains of the world, whereas the ancient, stable land area of India has remained practically immune from similar displacements. In some ways, ordinary macadam roads are analogous to rigid steel rails, in that changes of temperature cause buckling, while high-speed, wheeled traffic produces " creep." It would appear reasonable, by continuing the analogy to present practice, to use slightly separated, short lengths of sufficient weight, so that the passing traffic cannot impart an appreciable velocity to the mass. On this assumption, the most satisfactory way of protecting a macadam road would appear to be to cut it into sections by introducing deep ribs diagonal to the road. These ribs would localise the expansion and laterally deflect the tendency of the surface to " creep." The use of well-laid, heavy blocks of stone or concrete, arranged diagonally across the road, should also render a road immune from corrugations. If the blocks were 24 inches across, they would span the maximum corrugations which at present occur, the spaces between the blocks would allow of enough " play " for expansion, and the weight of the blocks would offer a heavy damping effect to the forces which cause displacement.

Paving Setts and Flags.—Besides possessing the properties of hardness, toughness and durability, stones used for setts or flags should wear uniformly and retain a rough surface. Coarse-textured rocks, or those with large, porphyritic crystals with marked differences of hardness between the mineral components, etc., are generally unsuitable for this purpose. The softer parts easily wear into holes under the impact and attrition of steel-studded tyres or the shoes of a heavy horse.

The medium- and fine-textured varieties of the igneous rocks make good paving setts, but they tend to become polished with wear and the road surface becomes slippery in consequence, particularly in wet weather.

Certain hard, felspathic sandstones and quartzites of medium-grained texture make ideal paving stones.

Although the felspar and quartz grains have approximately the same hardness, the easy cleavability of the felspar causes the grains of this mineral to break into angular fragments under impact, whereas the quartz grains are merely rounded. The scale of this wearing action is so small that the inequalities thus produced result in the surface of the stone remaining rough. A rock having a hard, strong matrix somewhat softer than the embedded quartz grains (as in the asphaltic, protecting carpet of tar-macadam roads) would answer the same purpose.

Some fine-grained marbles, calc-gneisses and some schistose rocks are of suitable texture and mineral composition to retain a rough surface when exposed to wear as paving stones. They are usually less resistant to abrasion than the hard felspathic sandstone flags which are so frequently used for paving purposes, and, as a result, these softer rocks are not serviceable in positions exposed to considerable wear. Many varieties of marble and some calc-gneisses make excellent ornamental flooring slabs, and are used for this purpose.

The extensive use of so-called patent stone is an indication that, with suitably-chosen ingredients, an artificial stone pavement can be prepared with excellent wearing properties, and often far more cheaply than could be prepared with natural stone. The uniformity of the artificial material can be guaranteed, and large floor slabs can be readily made.

Building Stone.—Strength and durability are the two most important considerations in choosing rock for building purposes. Particular characters of the stone may render it more suitable for one class of work than for another. Special features of a building may require stone of definite size and shape. Thus, the limitations of the many varieties of rock may soon be discovered when it becomes necessary to utilise such material to meet the requirements of engineering work. Almost any kind of rock can be used for ordinary building purposes if it is available in quantities. Some varieties are stronger and " dress " better than others. Coarse- or fine-textured types, provided thay are not unduly soft or friable, may answer equally well, and engineers are familiar with the commoner kinds. Problems arise when heavy structures are to be built or great columns or huge blocks are required, or when long slabs or thin sheets are wanted, and the material has to be specially quarried for the purpose.

From the remarks which have been made in the previous chapters or from personal experience of building stones, the engineer should not find it difficult to choose correctly the right kind of rock. He will be familiar with the fact that great blocks are generally only obtainable from coarse-textured, igneous rocks or from massive, sedimentary types. In these, the joint planes are further apart than in the fine-grained varieties. Generally, it is not easy to obtain large blocks suitable for columns from laminated beds or from thinly-banded types of rock. In exceptional cases, these rocks may be capable of dressing to columns, if their divisional planes (of lamination or banding) are not easily separable, as is the case in many gneisses and schists. On the other hand, if the rock can be easily parted along these planes, it may be possible to obtain thick slabs of stone.

The strength and durability of the quarried stone depends on the mineral components and their mode of aggregation. A rock with comparatively soft minerals—if these are interlocked with each other as in marble of uniform composition—has greater cohesion, and is therefore stronger and more durable than one in which the hard, mineral grains are uncemented and not interlocked, as is the case with some soft, friable sandstones.

In addition to the strength of a rock, its porosity and weathering qualities are frequently of considerable importance—particularly under certain conditions. Frosts are liable to cause the disintegration of some porous rocks. If a porous rock is wet, and while in this condition it is exposed to a severe frost, the expansive force of the ice which is formed in the interstices of the rock is liable to cause corners and sharp edges to break off and generally weaken the cohesion of the particles.

Important buildings which are to be built fire-proof should naturally be built of those materials which are least affected by heat or great changes of temperature. Limestones or marbles are unsuitable for this purpose, because, when strongly heated, they are calcined to lime, which, on slaking, falls to powder. Hard sandstones or quartzites have a great co-efficient of thermal expansion; consequently, when such material is exposed to fire, the expansion—besides loosening the joints and bonding—may result in such serious bulging of the walls as to cause a collapse of part of the building. Granite, if containing appreciable free quartz when exposed to great fluctuations of temperature, tends to become heavily fissured and disintegrated, due to the development of enormous internal strain. This, as explained in a previous chapter, is due to the great difference in thermal expansion of its principal minerals—quartz and felspar.

The exposed surfaces of rocks which are composed of relatively soluble constituents may, if used in buildings in manufacturing areas, be liable to severe corrosion by the acid vapours in the surrounding air. Many old houses or walls, etc., in London, which have been built of limestone, clearly show the effects of this corrosion.

Ornamental stones are usually chosen for their pleasing appearance. Great strength and durability are not always considered as essential qualities provided the stone is not unduly weak. However, since such rocks are often placed in exposed positions, they should have good weathering qualities and not become discoloured on exposure to rain and other atmospheric agencies. The presence of soluble salts such as gypsum or salt, or of minerals such as marcasite, which are liable to decomposition, should be sufficient reason for condemning an otherwise

attractive stone. The alteration products are usually coloured oxides, etc., which result in the appearance of iron stains or other ugly patches on the exposed surface of the ornamental stonework.

Preservatives for Building Stone.—It is necessary to state that no preservative will save a stone face from scaling or becoming friable if the rock itself is subjected to a greater stress than it can safely bear. On the one hand, the rock used in a building may be a decomposed variety of the type required and which, in consequence, is crushed. On the other hand, if the stonework is exposed to great alternations of temperature and the rock consists of minerals of different co-efficients of thermal expansion, it is evident that the only remedy is to plaster the facing—in which case, the use of brick might have saved the expense of dressing the stone. The appearance of an efflorescence from internal sources has already been treated in the chapter on buildings.

Preservatives may prevent a rock surface from absorbing moisture and subsequently "peeling" as a result of frost action. In other cases, the rock surface may be hardened against the solvent action of rain-water carrying deleterious chemical compounds. In some instances, if the preservative is used in the process of building, it may be possible to prevent the occurrence of an efflorescence on the wall faces. However, in most cases, the extra, recurring cost of the preservative might have been saved if the stone had been previously examined and more suitable material chosen.

The merits and limitations of the various preservatives—paint, water-glass, and the numerous other substances—are familiar to the engineer. His experience in their use will probably be the best guide in making a choice.

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